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State-of-the-Art Field Hydraulic Conductivity Testing of Compacted Soils

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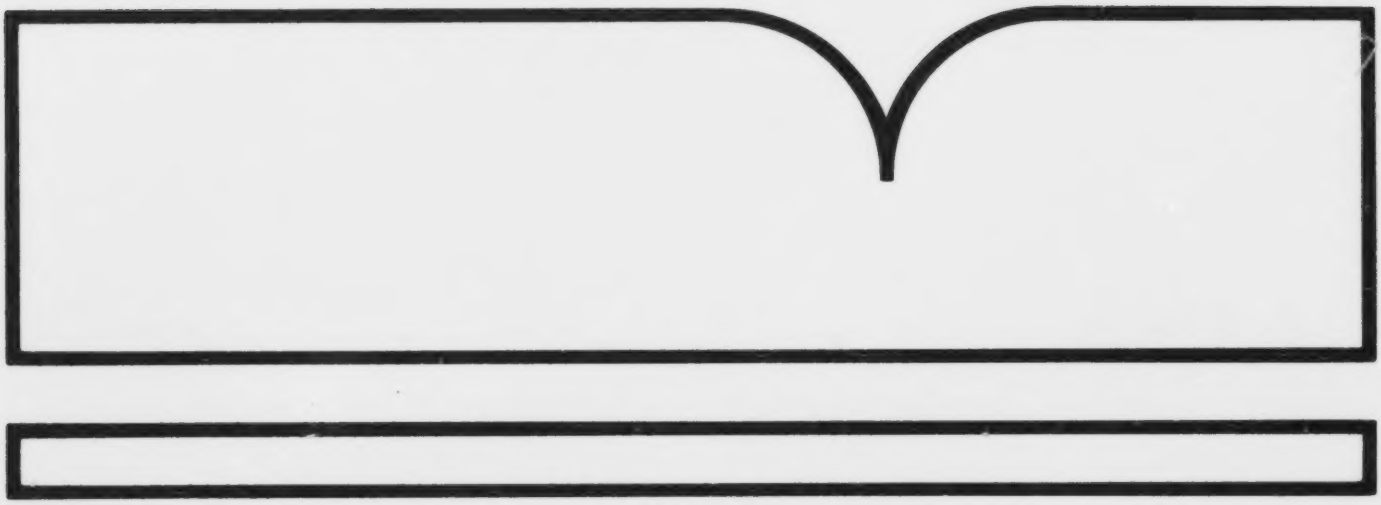

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16. ABSTRACT

This report documents the available technical information on field hydraulic conductivity test methods for soil liners. The methods discussed are currently used and readily available for determining the hydraulic conductivity of soils compacted in the field.

Hydraulic conductivity test methods currently used on soil liners were evaluated for their ability to meet the minimum requirements for field tests; i.e., that the test be capable of measuring hydraulic conductivities at least as low as 1×10^{-9} m/s and that the values obtained be representative of the overall soil liner. Of the few methods capable of meeting the minimum requirements, even fewer are both practical to use and rarely give false low values. Based on the advantages of the methods evaluated, the best and most practical currently available technologies for evaluating hydraulic conductivity are large single-ring infiltrometers and sealed double-ring infiltrometers.

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by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report documents the available technical information and current state-of-the-art of field hydraulic conductivity test methods for compacted soils. This information will be useful to those involved in policy development, research, design, construction, and monitoring of soils compacted for service as waste management system liners or infiltration barriers in cover systems.

E. Timothy Oppelt
Director
Risk Reduction Engineering Laboratory

ABSTRACT

The Congressionally mandated performance standard for soil liners of hazardous waste management facilities is a hydraulic conductivity of 1×10^{-9} m/s or less. In response to this statutory requirement, the U.S. Environmental Protection Agency has issued guidance requiring that facilities demonstrate this hydraulic conductivity in field tests.

Hydraulic conductivity test methods currently used on soil liners were evaluated for their ability to meet the minimum requirements for field tests; i.e., that the test be capable of measuring hydraulic conductivities at least as low as 1×10^{-9} m/s and that the values obtained be representative of the overall soil liner. Of the few methods capable of meeting the minimum requirements, even fewer are both practical to use and rarely give false low values. Based on the advantages of the methods evaluated, the best and most practical currently available technologies for evaluating hydraulic conductivity are large single-ring infiltrometers and sealed double-ring infiltrometers. If correction factors are needed to bring the values obtained with single-ring devices below 1×10^{-9} m/s, confirmatory tests should be conducted with sealed double-ring infiltrometers.

The size of infiltrometers used on soil liners should be at least 2 m^2. Also, at least three separate tests should be conducted on each test fill to allow characterization of the spatial variability in the soil liner.

A long-term study is needed to allow a comparative evaluation of candidate hydraulic conductivity testing devices. A large collection lysimeter should be incorporated into the study to give the true overall hydraulic conductivity value with which other values should be compared.

This report was submitted in fulfillment of contract number 68-03-3413 by K. W. Brown & Associates, Inc., subcontractor to PEI Associates, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from February 12, 1988 to May 14, 1989.

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SECTION 1

INTRODUCTION

In the Hazardous and Solid Waste Amendments (HSWA) of 1984, the Congress of the United States mandated that where compacted soil liners are used, their hydraulic conductivity shall be 1×10^{-9} m/s or less. In response to this statutory performance standard, U.S. Environmental Protection Agency (EPA) issued guidance requiring all proposed soil liners in hazardous waste management facilities to demonstrate this hydraulic conductivity in field tests. The intent of this requirement was to obtain accurate and realistic evaluations of how the compacted soil liner would perform under field conditions. Numerous studies have demonstrated that values obtained in laboratory hydraulic conductivity tests are not reliable indicators of the performance of soil liners under field conditions. No single study has been conducted, however, to document the range of field hydraulic conductivity test methods that are capable of adequately evaluating the field performance of a compacted soil liner.

Field hydraulic conductivity tests can damage soil liners in several ways. Such damage can occur in the form of holes drilled or trenches cut in the liner to facilitate the installation of testing equipment. Damage may also occur because field hydraulic conductivity tests can take as long as several weeks to complete, during which time both climatic events and weathering processes can substantially damage a soil liner (Rehage et al. 1986).

Intensive rainfall, dry periods, and freezes are examples of climatic events that can damage a soil liner. Weathering processes that can affect exposed soil liners include shrinking and swelling caused by moisture fluctuations, evaporative drying, or freeze-thaw cycles. For avoidance of damage due to prolonged exposure, a soil liner should be covered with protective layers immediately after its construction. This need for immediate covering of a soil liner makes it difficult to conduct field hydraulic conductivity tests. Consequently, the EPA (1985) recommended that field hydraulic conductivity tests be conducted on a test fill.

A test fill is a test section of a soil liner constructed with the soil and equipment and by the same procedures used in the construction of an actual soil liner. Its primary function is to serve as a facility where testing can be conducted to verify that the specified hydraulic conductivity values can actually be achieved with a full-scale liner. For the data generated from the test fill to be useful, the quality assurance testing on the test fill must be well documented, and construction of the

test fill must be the same as that used for the full-scale facility (U.S. EPA 1986). In addition, both the test fill and the hydraulic conductivity tests used on the test fill should provide a sound basis for meeting the following objectives:

1) Accurately measuring hydraulic conductivities of 1×10^{-9} m/s and lower.

2) Obtaining hydraulic conductivity values that accurately represent the properties of the full-scale soil liner.

It is especially important that the hydraulic conductivity values obtained be representative of the full-scale soil liner. Rogowski et al. (1984) defined the representative elementary volume (REV) of a soil liner as the smallest volume above which the variance no longer decreases significantly. The REV will be different for every liner and will be highly dependent on the natural variability of the soil material and the level of quality assurance exercised during construction of the soil liner. At least three field hydraulic conductivity tests will be required to define the REV for a given soil liner.

This report documents the available technical information on field hydraulic conductivity test methods for soil liners. The methods discussed are currently used and readily available for determining the hydraulic conductivity of soils compacted in the field.

Section 2 summarizes the findings and specifies which field hydraulic conductivity methods meet the minimum requirements for evaluating soil liners. Section 3 presents general recommendations regarding areas in which additional study is needed.

Section 4 discusses all the applicable field hydraulic conductivity methods and the parameters used to characterize the selected methods for measuring hydraulic conductivity.

SECTION 2

CONCLUSIONS

Various methods are currently being used to evaluate the field hydraulic conductivity of soil liners. Only a few of these methods, however, can reliably meet the following requirements for evaluating soil liners:

1) A method should be capable of accurately measuring hydraulic conductivities of 1×10^{-9} m/s and lower.

2) The values obtained should be representative of the overall hydraulic conductivity of a soil liner.

Of the few methods capable of meeting the preceding minimum requirements, even fewer are relatively simple to use, rarely give false low values, and provide definitive results in a reasonable time frame. Key findings of each method evaluated are summarized in the following paragraphs.

Air-entry permeameters can give rapid field measurements of vertical hydraulic conductivity. They involve the introduction of water into a sealed test ring and the measurement of changes in volume of water in a graduated supply reservoir. After the wetting front advances into the soil, the water supply is cut off and the resulting maximum suction is measured. The saturated hydraulic conductivity is calculated from a combination of the depth to the wetting front and the maximum suction values. This method can measure hydraulic conductivity values of 1×10^{-9} m/s and lower, but it may not test a large enough area to give values representative of the overall soil liner.

Borehole methods such as the Guelph and Boutwell permeameters are in-hole methods for measuring steady-state infiltration into unsaturated soil. The Guelph permeameter uses a constant head and can account for the pressure, gravity, and soil capillarity components of flow. The Boutwell permeameter can determine both vertical and horizontal hydraulic conductivity of a soil liner. Both methods can measure hydraulic conductivities as low as 1×10^{-9} m/s. Neither method, however, tests a large enough area of a soil liner to give reliable hydraulic conductivity values that are representative of the overall soil liner.

Porous probe methods such as the BAT permeameter typically use a cone-shaped porous probe to provide a hydraulic connection with the soil pores. A pressure transducer is used to measure gas pressure in a test container

that is connected to the porous probe. When water flows out of the container and into the soil pores, the pressure change in the container is recorded and used to calculate hydraulic conductivity. This method has been used to measure hydraulic conductivities less than 1×10^{-9} m/s on soil liners. The method does not, however, test an area of the soil liner large enough to give reliable hydraulic conductivity values representative of the overall soil liner.

The ASTM double-ring infiltrometers use an outer ring to ensure the inner ring measures only the vertical hydraulic conductivity of a soil. This method has not been shown to be capable of either measuring hydraulic conductivity values of less than 1×10^{-8} m/s or obtaining values representative of an overall soil liner.

The standard ASTM double-ring equipment has been modified to permit the measurement of hydraulic conductivities as low as 1×10^{-9} m/s. The size of the inner ring, however, is too small to give reliable hydraulic conductivity values that are representative of an overall soil liner.

Box infiltrometers use an array of sealed boxes that can measure hydraulic conductivities as low as 5×10^{-10} m/s. The aggregate area evaluated by an array of four infiltrometers (1.44 m^2) appeared to be sufficient to obtain representative values for hydraulic conductivity on a soil liner that had received a high level of quality assurance per unit area. The array of infiltrometers also was able to define the spatial variability of the soil liner. The primary disadvantages of this method are that it is difficult to use and that skilled personnel would definitely be required for installation, monitoring, data collection, and data analysis.

Single-ring infiltrometers measure the infiltration of water ponded inside a large-diameter ring pressed into a soil liner. These infiltrometers can measure hydraulic conductivities less than 1×10^{-9} m/s. If the ring covers an area of at least 2 m^2, it should be capable of obtaining values representative of the overall soil liner. Care should be taken not to rely on correction factors to reduce the hydraulic conductivity values below 1×10^{-9} m/s.

Sealed double-ring infiltrometers can use a relatively large inner ring (2.3 m^2) to measure infiltration. So configured, this method has received substantial field testing and has a demonstrated capability both to measure hydraulic conductivity values below 1×10^{-9} m/s and to obtain values representative of the overall soil liner. The method requires more installation time than many methods, but it has the advantages of both few ambiguities in the experimental method and few possibilities for yielding false low values. Care should be taken not to scour the soil liner surface when water is placed in the sealed inner ring, and temperature fluctuations should be kept to a minimum.

Collection lysimeters collect and measure the volume of liquid percolating through a defined area of a soil liner. These systems are capable of measuring hydraulic conductivities of less than 1×10^{-9} m/s and

of obtaining values representative of an overall soil liner. These tests can, however, be time-consuming, and they may require skilled personnel. They are relatively expensive to install, and great care should be taken not to damage the flexible membrane that is used to collect the underdrainage. Ultimately, this method has the potential for yielding the most accurate values for hydraulic conductivity of a soil liner. In practice, however, the response time of a collection lysimeter limits its utility for short-term tests.

Velocity permeameters use a small computer to determine in situ hydraulic conductivity from a falling-head infiltrometer. The method has yet to be tested on compacted soil liners, and further tests are needed to determine if it is capable of measuring hydraulic conductivities of less than 1×10^{-9} m/s. As currently designed, the method evaluates too small an area to give hydraulic conductivity values representative of an overall soil liner.

Porous plate infiltrometers use water infiltration under tension to estimate hydraulic conductivity. In currently available porous plate infiltrometers, the area evaluated is too small to obtain hydraulic conductivities representative of an overall soil liner. No data are yet available on the use of this method on soils with hydraulic conductivities less than 1×10^{-9} m/s. Research with this method is ongoing, and it appears to have promise for distinguishing between overall field hydraulic conductivity and the component of flow occurring through macropores.

Cores can be collected from a soil liner and used in a variety of laboratory hydraulic conductivity tests. These tests are usually capable of measuring hydraulic conductivity values less than 1×10^{-9} m/s. Laboratory samples, however, are typically too small to yield hydraulic conductivity values representative of the overall soil liner.

SECTION 3

RECOMMENDATIONS

To maximize the probability of obtaining a hydraulic conductivity value that is representative of the overall soil liner, a test method should have the following qualities:

1) The ability to measure accurately hydraulic conductivities of less than 1×10^{-9} m/s.

2) Minimal requirements for skilled personnel during installation, operation, data acquisition, data reduction, and interpretation of results.

3) Few ambiguities in the experimental method and few possibilities for yielding false low values.

4) Inexpensive enough to allow at least three replicate tests to determine spatial variability of field hydraulic conductivity.

5) Sufficient area of coverage for each replicate test to ensure that a statistically sound average number of macropores per unit area is covered.

6) Sufficiently short time required to conduct each test to ensure that it is practical for use.

Not all of these qualities are quantifiable, given the current state of knowledge on hydraulic conductivity test methods and soil liners. It is possible, however, to pinpoint where additional study is needed and to suggest the best currently available methods.

For a better definition of the test methods that would maximize the probability of obtaining representative hydraulic conductivity values for soil liners, a long-term soil-liner study incorporating both a large collection lysimeter (to give true overall hydraulic conductivity) and an array of candidate hydraulic conductivity testing devices is recommended. The results could be used to define the reliability of testing devices and to characterize their sensitivity to spatial variability within the soil liner. Ideally, several sized versions of each test method should be used in each arrangement to obtain a better understanding of the minimum size requirement for the test devices.

Based on the advantages and disadvantages of all the methods reviewed in this document, the best and most practical currently available technologies for evaluating field hydraulic conductivity are as follows:

1) Single-ring infiltrometers covering an area greater than 2 m^2.

2) Sealed double-ring infiltrometer with an inner ring covering an area greater than 2 m^2.

Until conclusive studies are completed, it is recommended that correction factors (such as those commonly used with single-ring devices) not be relied upon to reduce hydraulic conductivity values below 1×10^{-9} m/s. Correction factors for evaporative losses also should be avoided. If the uncorrected hydraulic conductivity values are higher than the maximum allowable value (1×10^{-9} m/s), confirmatory tests should be conducted with sealed double-ring infiltrometers.

Spatial variability of the soil liner must be characterized to ensure the hydraulic conductivity values obtained are representative. At least three field hydraulic conductivity tests should be conducted, and the values obtained from all three should be 1×10^{-9} m/s or less. Averaging of values should not be allowed as a means of bringing values below 1×10^{-9} m/s.

SECTION 4

FIELD HYDRAULIC CONDUCTIVITY METHODS

This section presents the field methods for measuring soil hydraulic conductivity and evaluates the applicability of the methods for determining hydraulic conductivity of compacted soil liners. The methods discussed are those currently used to determine field infiltration, hydraulic conductivity, or underdrainage rates for soils with low hydraulic conductivity values.

A wide variety of field hydraulic conductivity methods have been published in the scientific and engineering literature. Many of these methods are not adequate for evaluating soil liners because they can neither measure very low hydraulic conductivities nor evaluate a large enough area to give values representative of the overall liner. Other methods are adequate to obtain representative values on low-hydraulic-conductivity soils, but they are complex and time-consuming, or they require considerable effort on the part of skilled equipment operators. Some other methods appear to give accurate and representative values without the need for extensive involvement of skilled operators. The purpose of this section is to provide sufficient detail on each field hydraulic conductivity method to determine which methods can provide a reliable evaluation of soil liner performance.

Each subsection on a field hydraulic conductivity method begins with a brief introduction and a discussion of the underlying principles and test conditions. Details are then provided on the specific test methodology, including a list of all required apparatus, a summary of procedures used in the method, calculations used to determine hydraulic conductivity, and applicable quality assurance measures. Example data that may be generated by the method are then presented. Finally, the subsection includes comments on the advantages, disadvantages, and general applicability of the method for testing the hydraulic conductivity of soil liners.

AIR-ENTRY PERMEAMETERS

Air-entry permeameters are used for rapid field measurements of vertical hydraulic conductivity in initially unsaturated soil (Bouwer 1978). This method uses Darcy's fundamental law for water flow through soil to determine soil hydraulic conductivity above a water table.

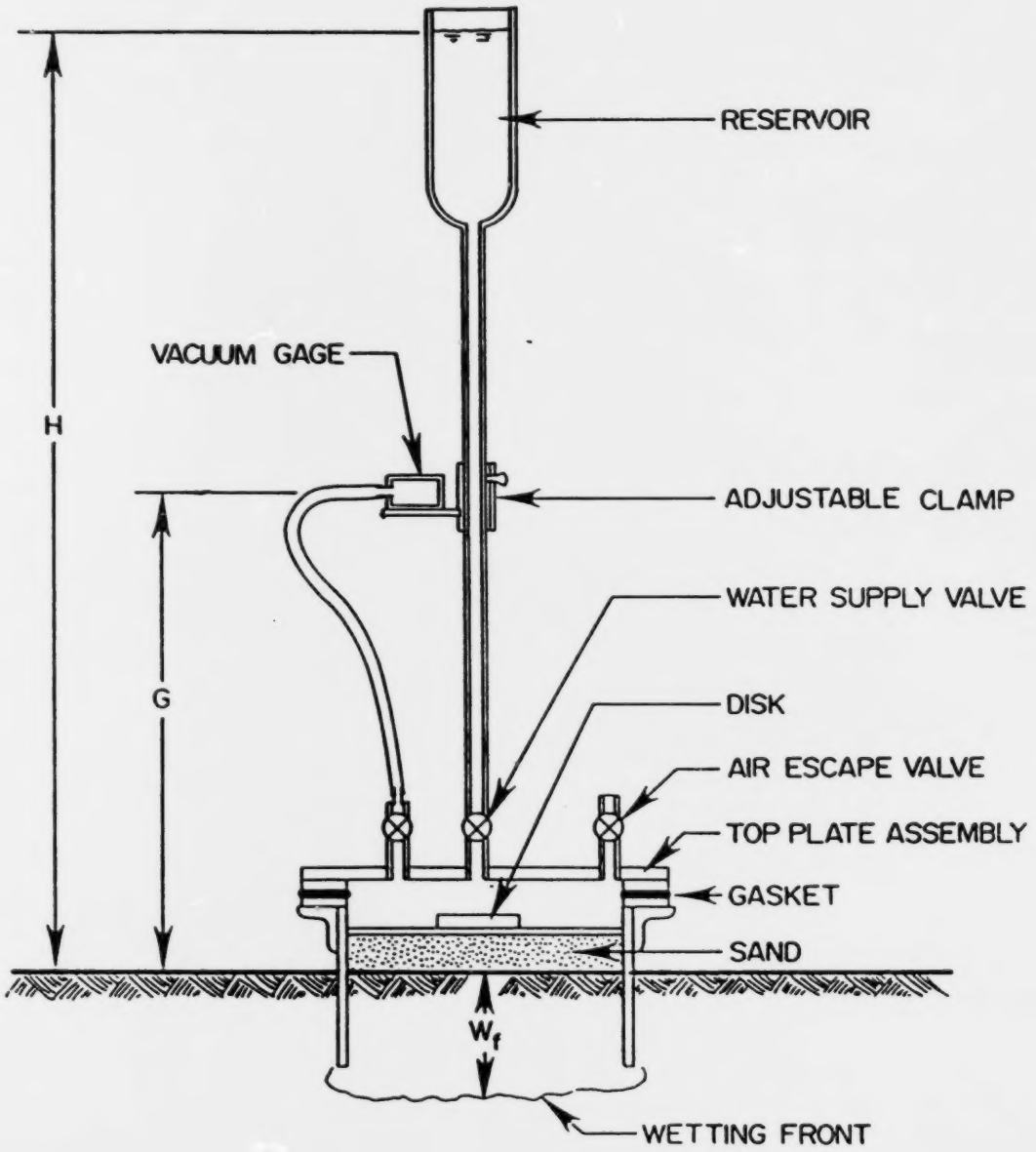


FIGURE 1. DIAGRAM OF THE EQUIPMENT FOR THE AIR-ENTRY PERMEAMETER TECHNIQUE (BOUWER 1978).

6) Open the water supply valve.

7) Close air escape valve when all air has been driven out of the system.

8) Measure infiltration rate by recording change in volume of water in the reservoir over time.

9) Close the water-supply valve to halt the movement of the wetting front.

10) Open the vacuum gauge valve to measure the pressure inside the cylinder. Convert the reading into meters and insert into Equation 1.

11) Record the minimum pressure and immediately remove the equipment to determine the depth of the wetting front.

12) Determine the depth of wetting by the tensiometer method or by the digging and visual examination method.

Calculations--

Equation 1 is used to calculate the hydraulic conductivity at the wetting front:

$$K = \frac{W_f \times Q}{A \times (H + W_f - 0.5\ P_a)} \qquad (1)$$

where K = hydraulic conductivity, m s^{-1}
W_f = depth of the wetting front, m
Q = water flow rate just before supply valve was closed, m^3/s
P_a = air-entry pressure of the soil = $(p_m + G + W_f)$, m of water
P_m = minimum pressure head as determined by the maximum reading on vacuum gauge, m
H = height of water level above the soil, m
A = area of test ring, m^2
G = height of gauge above soil surface, m

For most soil liners, the saturated hydraulic conductivity is estimated by multiplying the wetting front conductivity value by a factor of four (Bouwer 1966). Some air is entrapped in the soil medium during the short test period, and the factor of four was recommended to account for the entrapped air, which could make the saturated hydraulic conductivity less than the actual value.

Quality Assurance--

Aldabagh and Beer (1971) used the air-entry permeameter to determine hydraulic conductivity of loam to silty clay loam soils. The results indicated that 11 composite hydraulic conductivity values determined from randomly spaced areas were needed to give average values within 20 percent of the true mean value. These researchers recommended the use of a larger

number of determinations of composite hydraulic conductivity values than the 11 estimated in their work.

The accuracy of measuring the depth of the wetting front (W_f) can have a significant effect on the accuracy of the calculated hydraulic conductivity. Recent studies showed that several compacted materials with hydraulic conductivities of 1×10^{-9} m/s and lower had effective porosities of 10 to 20 percent of the total porosities (Horton et al. 1988). If the depth to the wetting front is measured in a small area, such as with tensiometers, then the value obtained may not accurately reflect the overall average depth to the wetting front. Of the two methods for determining W_f, visual examination of a large cross-section of soil, as recommended by Bouwer (1978), would appear to be the more accurate means.

Example Data

Knight and Haile (1984) used air-entry permeameters to estimate the field and laboratory hydraulic conductivity on a soil liner in northern Saskatchewan, Canada. The tests were performed as part of quality control on a compacted mixture of natural till and bentonite. Of the 133 tests carried out in the field, 35 gave hydraulic conductivity values that were higher than the design objective of 1×10^{-9} m/s. The authors attributed the high values to leaks around the perimeter of the test ring.

Haile and Brown (1988) used a 0.6-m-diameter air-entry permeameter (AEP) to determine the hydraulic conductivity of the compacted clay soil liners of heap leach pads at two sites in California. Comparison with data from sealed double-ring infiltrometers (SDRI) and laboratory air-entry permeameters showed agreement with the values obtained by these methods (Table 1). The data indicated that AEP can be used to measure hydraulic conductivities of 1×10^{-9} m/s or lower.

Nordquist et al. (1986) measured field and laboratory hydraulic conductivity of compacted clay liners at three test fills. Air-entry permeameters were used to determine the field hydraulic conductivity of the test fill liner. The averages of the field and laboratory hydraulic conductivity test results were within one order of magnitude (Table 2).

Comments

The air-entry permeameter method can rapidly measure field hydraulic conductivity values of 1×10^{-9} m/s and lower. Aldabagh and Beer (1971) indicated that 0.3 to 1 hour is needed to run the test, depending on the temperature of the water and the hydraulic conductivity of the soil. A shortcoming of this method, however, is that it tests a small area of soil (0.3 m^2) and therefore may not reflect the effect of soil macropores on hydraulic conductivity. Soil macropores that are widely spaced in a soil liner can have a pronounced effect on hydraulic conductivity. McKeague et al. (1982) discussed some of the problems encountered when this method is used in the presence of macropores in the soil.

TABLE 1. HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY SOILS AT TWO HEAP LEACH PADS IN CALIFORNIA[a]

Site	Method	Hydraulic Conductivity, m/s Test Fill 1	Test Fill 2	Test Fill 3
Jamestown Mine	In situ AEP (10 tests/fill)	1.4×10^{-9}	6.2×10^{-9}	1.0×10^{-9}
	SDRI	1.2×10^{-9}	3.7×10^{-9}	1.2×10^{-9}
	Lab AEP (10 tests/fill)	2.6×10^{-9}	1.9×10^{-9}	6.4×10^{-10}
	Full-scale liner (13 ha)			
	In situ AEP (13 tests)		2.6×10^{-9}	
	Lab AEP (15 tests)		2.5×10^{-9}	
Carson Hill	In situ AEP (9 tests)		7.0×10^{-10}	
	SDRI		9.0×10^{-10}	

[a] Source: Haile and Brown 1988

TABLE 2. FIELD HYDRAULIC CONDUCTIVITY DATA OBTAINED BY USING AIR-ENTRY PERMEAMETER AND LABORATORY PERMEABILITY TEST WITH SHELBY TUBE SAMPLES

Type of test	Liner	Number of tests	Hydraulic Conductivity, m/s Range	Average
Air-entry permeameter	1	15	8×10^{-11} to 8×10^{-10}	3×10^{-10}
	2	45	7×10^{-11} to 1×10^{-9}	3×10^{-10}
	3	20	1×10^{-10} to 8×10^{-10}	3×10^{-10}
Laboratory permeameter (Fixed-wall)	1	6	2×10^{-10} to 4×10^{-10}	3×10^{-10}
	2	11	3×10^{-11} to 1×10^{-9}	3×10^{-10}
	3	9	3×10^{-10} to 1×10^{-9}	2×10^{-10}

Air-entry permeameters can be used to obtain the vertical hydraulic conductivity of one lift in a compacted soil liner, as well as that of the entire thickness of soil liner. The data may be inaccurate, however, because of either inadequate sealing between the cylinder and the soil or errors in determining the exact locations of the wetting front. Air-entry permeameters are easy to transport to the field and to use. In addition, the method is not labor-intensive (i.e., two men can set up the equipment and make the measurements).

BOREHOLE METHODS

Several borehole methods have been used to measure the hydraulic conductivity of soils. Borehole permeameters are essentially in-hole constant-head or falling-head permeameters. The methods involve measuring the steady-state infiltration rate of water into unsaturated soil from a cylindrical borehole. Two borehole methods that have been used to test the hydraulic conductivity of soil liners are Guelph (Reynolds and Elrick 1986) and Boutwell permeameters (Boutwell and Derric 1986). The Guelph permeameter uses a Mariotte siphon to maintain a constant head of water within the borehole. The Boutwell permeameter, however, involves an evaluation of the flow into a cased borehole and an evaluation of subsequent flow after the addition of an uncased extension to the hole. Details of these two methods are discussed in the following subsections.

Guelph Permeameter

Principles--

The Guelph permeameter uses a Mariotte siphon over a 0.02- to 0.05-m diameter well to measure the steady-state infiltration rate of water into unsaturated soil. The in-hole Mariotte bottle device is used to establish and maintain a constant head of 0.05 to 0.35 m within the borehole and to measure the corresponding flow rate. Two or more data pairs of the constant head and flow rate are recorded for each hole and substituted into equations to obtain field-saturated hydraulic conductivity, sorptivity, and the relationship between the hydraulic conductivity and the pressure head.

Method--

Apparatus--A schematic of the Guelph permeameter is shown in Figure 2. The main components are as follows:

1) Air-inlet tube.

2) Reservoir cap.

3) Calibrated inner reservoir tube.

4) Calibrated outer reservoir tube.

5) Outer reservoir outlet port.

6) Permeameter tip with rubber stopper on the end.

7) Sliding air-tight seals.

8) Tripod assembly.

Procedure--The procedure used is as follows:

1) Using a soil auger, excavate a borehole of radius "a" to the desired depth in the soil to be tested.

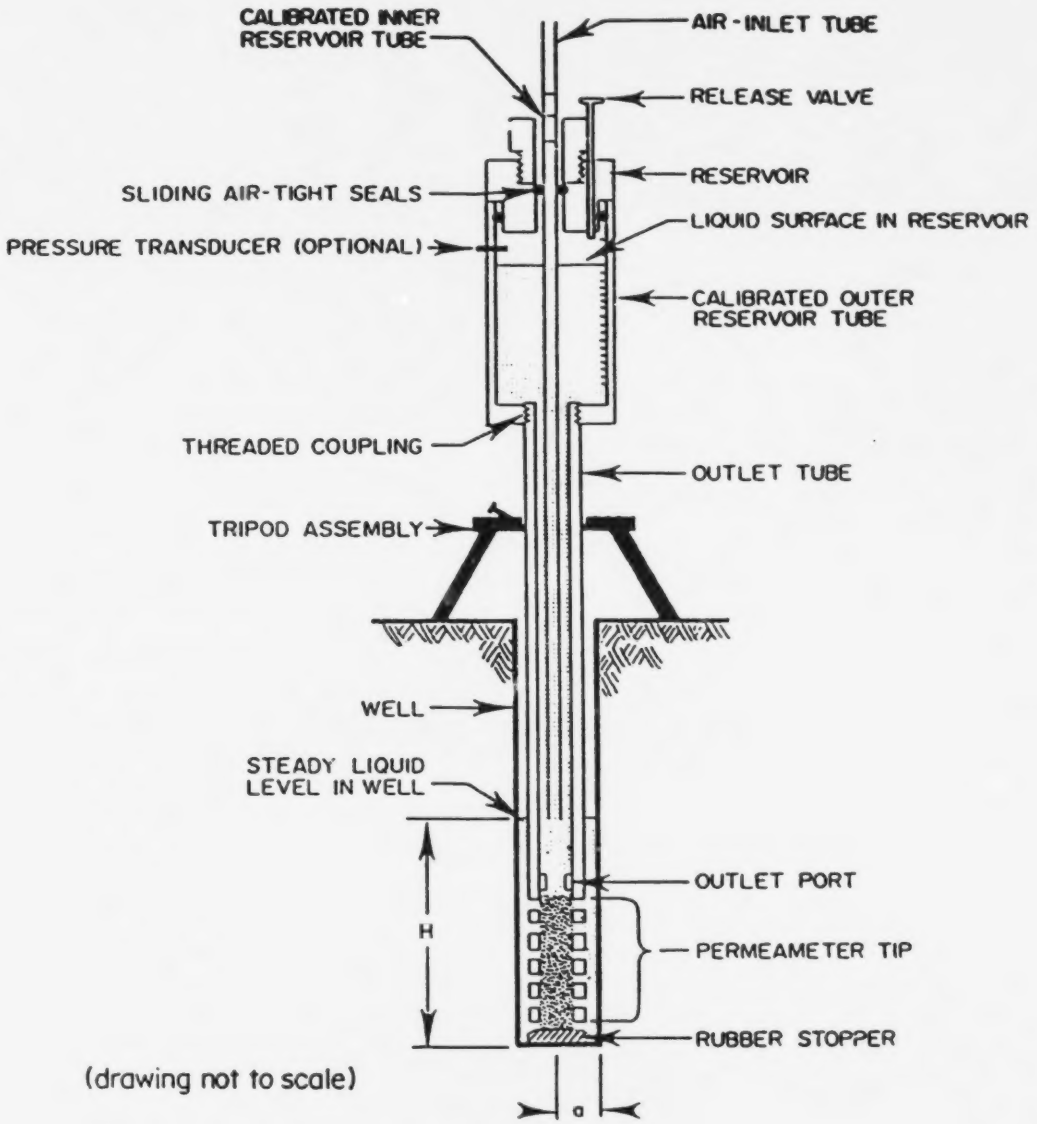


FIGURE 2. SCHEMATIC OF THE GUELPH PERMEAMETER (REYNOLDS AND ELRICK 1986).

2) Assemble the permeameter.

3) Fill inner and outer reservoir tubes with liquid.

4) Place permeameter in borehole.

5) Start permeameter by raising the air-inlet tube out of the outlet port.

6) Set the desired head of water (H) by adjusting the height of the air-inlet tube.

7) Monitor the rate of fall of the liquid surface in the outer reservoir tube (R) until a steady rate is attained.

8) Calculate the steady-state volumetric flow rate (Q) by multiplying the rate of fall of the liquid surface (R) by the annular cross-sectional area between the air-inlet tube and the reservoir tube.

9) Calculate H/a and use the value to select the proportionality constant (C) from Figure 3.

10) Calculate the field saturated hydraulic conductivity by using either the simultaneous equation approach or the least-squares approach.

The simultaneous equation approach (Richards analysis) is used to calculate the hydraulic conductivity by solving Equation 2. This involves repeating steps 7 through 10 at least once because the simultaneous equations require at least two values of H and Q. The least-squares approach uses two or more H-levels and the corresponding Q values (Reynolds and Elrick 1985a) to solve Equation 3.

Calculations--Reynolds and Elrick (1985b) presented an equation to describe the steady-state discharge from a cylindrical well into unsaturated soil. The equation incorporates the parameters for pressure, gravity, and soil capillarity.

$$\underset{\text{PRESSURE}}{2\pi H^2 K_{fs}} + \underset{\text{GRAVITY}}{C\pi a^2 K_{fs}} + \underset{\text{CAPILLARITY}}{2\pi H o_m \phi} = C\,Q \qquad (2)$$

where H = steady depth of liquid in borehole, m
K_{fs} = field saturated hydraulic conductivity, m/s
C = dimensionless proportionality constant dependent on H/a
a = borehole radius, m
ϕ_m = matric flux potential, m^2/s
Q = steady-state volumetric flow rate of liquid, m^3/s

Reynolds and Elrick (1986) and Baumgartner et al. (1987) provided a simultaneous equation approach for solving Equation 2. The approach involves measuring two or more steady volumetric flow rates (e.g., Q_1 and

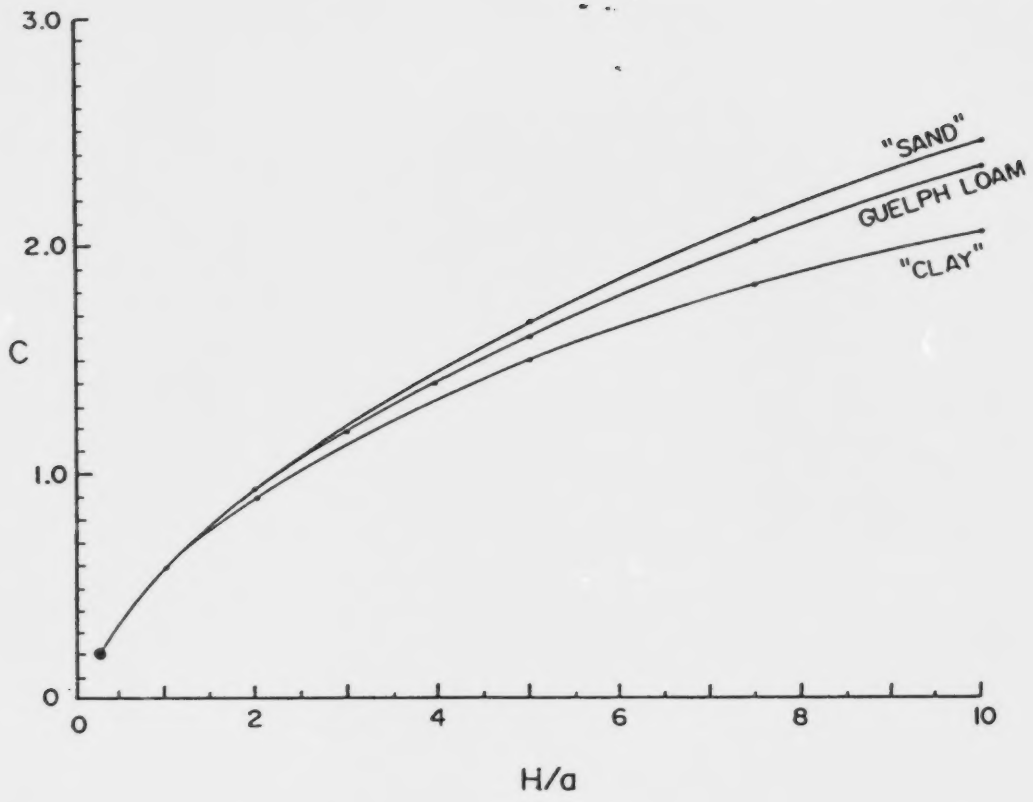


FIGURE 3. C VERSUS H/a RELATIONSHIP FOR A RANGE OF SOIL TEXTURES (REYNOLDS AND ELRICK 1985 b).

Q_2)) and their corresponding steady depth of liquid in the borehole (e.g., H_1 and H_2). After H_1, H_2, Q_1 and Q_2 have been substituted into Equation 2, ϕ_m is eliminated from the two equations formed. The resulting equation is then simplified to the following form:

$$K_{fs} = G_2 Q_2 - G_1 Q_1 \tag{3}$$

where

$$G_1 = \frac{H_2 C_1}{\pi[2H_1H_2(H_2 - H_1) + a^2(H_1C_2 - H_2C_1)]}$$

$$G_2 = \frac{H_1 C_2}{\pi[2H_1H_2(H_2 - H_1) + a^2(H_1C_2 - H_2C_1)]}$$

The appropriate C values for H_1 and H_2 are C_1 and C_2, respectively.

The value of the dimensionless proportionality constant (C) is obtained from Figure 3, which gives C curves for three classes of soils. These curves apply to soils at field capacity or drier. Most loams and structured clay soils are represented by the Guelph loam soil. The matric flux potential is defined by Gardner (1958) as:

$$\phi_m = \int_{\psi i} K_{(\psi)} \, d\psi \tag{4}$$

where $K_{(\psi)}$ = hydraulic conductivity-pressure head relationship, m/s
ψi = initial (assumed uniform) pressure head in the soil, m
ϕ_m = matric flux potential, m^2/s

Simpler and less labor-intensive approximations of hydraulic conductivity can be made by using the analysis of Laplace with only one H-level determination. The following is the form of the Laplace equation used to determine hydraulic conductivity (K_{fs}):

$$K_{fs} = \frac{C Q}{(2\pi H^2 + C\pi a^2)} \tag{5}$$

where H = steady depth of liquid in borehole, m
K_{fs} = field saturated hydraulic conductivity, m/s
C = dimensionless proportionality constant dependent on H/a
a = borehole radius, m
Q = steady-state volumetric flow rate of liquid, m^3/s

Quality Assurance--The Guelph method gives "point" measurements. Several readings are needed to ensure that the data obtained from a given location accurately represent the hydraulic conductivity of that area.

A heterogeneous porous medium can give erroneous hydraulic conductivity values. The presence of a large macropore will give a negative hydraulic conductivity value when tests are done at two constant water levels in the borehole (H-levels) and the resulting data are used in the simultaneous equation approach to calculate the hydraulic conductivity.

Smearing of the soil on the surfaces of the borehole will give low values of K_{fs} that are not representative of the overall soil. Reynolds and Elrick (1986) found a wire brush was useful for removing the smeared soil.

Example Data--

Bradshaw (1986) used a Guelph permeameter to measure hydraulic conductivity in a silty clay soil at an initial water content of 37 percent. Fifty-eight measurements of flow rates in 20 test holes indicated the geometric mean of the field-saturated hydraulic conductivity to be 7.0×10^{-9} m/s with a multiplier/divider factor of 1.85 for the standard deviation (using Laplace analysis). Fifty percent of these test holes provided usable data for the simultaneous equation analysis (Baumgartner et al. 1987). The geometric mean for the simultaneous equation analysis was 2.2×10^{-9} m/s, with a standard deviation factor of 2.1.

Table 3 presents a comparison of the Guelph permeameter method (using Laplace analysis) with the air-entry permeameter method and a soil core method on a range of soil types (Reynolds and Elrick 1985b). The data indicated hydraulic conductivity determined by the air-entry and Guelph methods were one order of magnitude higher than the data from the soil core method for fine sand to clay soils.

Stephens et al. (1988) presented data that compared the Guelph permeameter with experimental borehole ponding data and air-entry permeameter data. Comparison of these data (Table 4) indicated a general agreement of the hydraulic conductivity values determined by these methods. The comparison was made on soils with much higher hydraulic conductivities than clay. Further studies are needed to determine the extent to which values will agree on low-hydraulic-conductivity materials such as compacted soil liners.

Comments--

Guelph permeameters have not been widely used to determine hydraulic conductivity on compacted soil liners. Studies conducted on low hydraulic conductivity soils indicated, however, that the instrument is capable of measuring values as low as 2×10^{-9} m/s. For provision of reliable data at the regulatory limit of 1×10^{-9} m/s, a method should be able to provide credible data below this limit.

Another shortcoming of the Guelph permeameter is that it only evaluates a small area of soil (3×10^{-4} to $2 \times 10^{-3} m^2$). For this reason, the method is unlikely to give values that are representative of the overall field hydraulic conductivity. There are currently no data available to assess the number of tests that would be necessary to obtain representative values.

TABLE 3. COMPARISON OF THREE METHODS OF DETERMINING SATURATED HYDRAULIC CONDUCTIVITY--GUELPH PERMEAMETER, AIR-ENTRY PERMEAMETER, AND SOIL CORE[a]

Soil Type	Method[b]	Saturated hydraulic conductivity, 10^{-6} m/s
Fox loamy sand	AEP	33.70
	GP	57.60
	SC	20.60
Vineland vfs loam	AEP	4.06
	GP	1.89
	SC	0.74
Wollwich silty loam	AEP	2.70
	GP	1.86
	SC	0.62
Trafalgar clay	AEP	0.202
	GP	0.106
	SC	0.025

[a] Source: Reynolds and Elrick 1985b
[b] AEP = Air-entry permeameter
GP = Guelph permeameter
SC = Soil core

TABLE 4. COMPARISON OF SATURATED HYDRAULIC CONDUCTIVITY DATA FROM GUELPH, BOREHOLE, AND AIR-ENTRY PERMEAMETERS[a]

Method	Saturated hydraulic conductivity, m/s
Guelph	1.1×10^{-8}
	2.3×10^{-8}
	3.5×10^{-9}
Borehole	1.1×10^{-8}
	7.7×10^{-9}
Air-entry	7.7×10^{-10} to 1.4×10^{-9}

[a] Source: Stephens et al. 1988

Auger equipment tends to smear the walls of a borehole excavated in moist-to-wet clay soils. Smearing partially seals the borehole surfaces, which results in flow rates that are too low to be representative of the soil. Thus, removal of a smear-layer is critical to obtaining quality data with the Guelph permeameter method. Reynolds and Elrick (1986) found the efficiency of smear-layer removal declined with increasing wetness of clay soils. Soil liners in waste-management facilities are typically compacted at moisture contents that would cause smearing.

Determination of hydraulic conductivity for compacted soils by the Guelph permeameter method is difficult because the instrument is not sufficiently sensitive to measure the small volumes of water involved. For example, hydraulic conductivity near the regulatory maximum of 1×10^{-9} m/s, measured changes in water volume would be approximately 0.2 cm^3/h at the H values typically used with the device. In addition, at such low flow rates, the volume of water evaporated from the instrument could be a major source of error.

Boutwell Method

Principles--

The Boutwell method is a two-stage borehole hydraulic conductivity test capable of determining both vertical and horizontal hydraulic conductivity of a soil. In stage one, hydraulic conductivity is determined by casing a borehole and measuring flow through the bottom of the borehole (K_1). In stage two, the length of the borehole is extended but the casing is not. This allows flow through both the bottom and the uncased sidewalls of the borehole (K_2) to be measured. These two hydraulic conductivity values can then be used to calculate both horizontal and vertical hydraulic conductivity, as shown in calculations presented later in this subsection.

Method--

Apparatus--Figure 4 is a schematic of the Boutwell borehole method. The following apparatuses are needed for this method:

1) An auger or other device suitable for excavating a borehole at least seven times deeper than the diameter of the hole.

2) Borehole casing.

3) Graduated standpipe.

Procedures--Procedures for the Boutwell method of determining hydraulic conductivity are summarized here.

1) Auger to a depth five times the diameter of the borehole.

2) Place a casing inside the borehole and seal the space between the casing and the borehole with grout.

3) Fill the casing and standpipe with water and cover the open end of the standpipe to prevent evaporation.

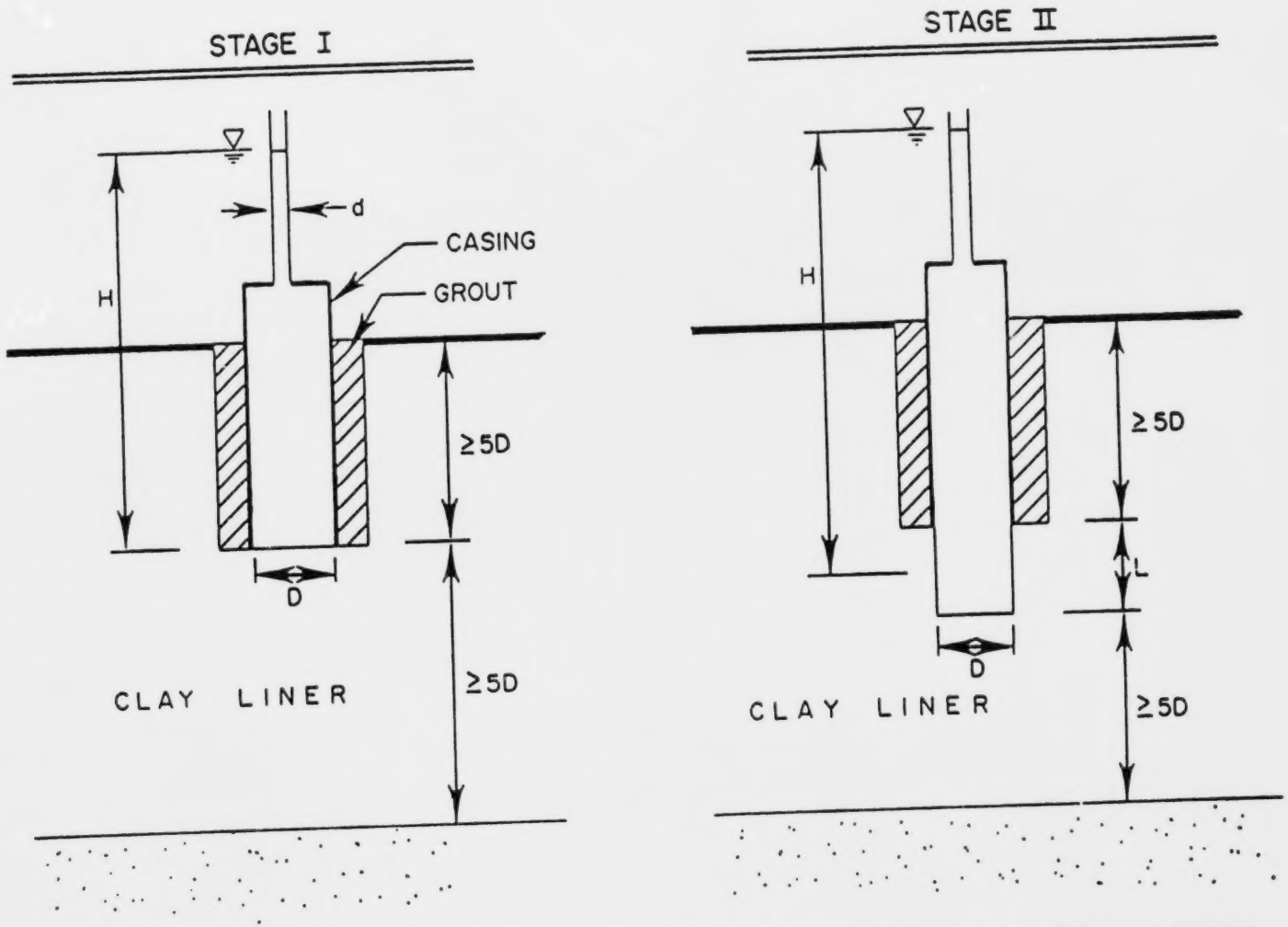


FIGURE 4. SCHEMATIC DIAGRAM OF THE BOUTWELL BOREHOLE PERMEAMETER (BOUTWELL & DERRIC 1986).

4) Measure a series of flow rates and calculate K_1 (Equation 6); plot the values of K_1 as a function of time until steady conditions are reached.

5) Remove the top of the permeameter and deepen the hole with an auger or a suitable thin-walled sampling tube; the ratio of L/D in the uncased zone should be between 1 and 1.5.

6) Reassemble the permeameter and perform the falling-head test again.

7) Measure a series of flow rates and calculate K_2 (Equation 7); plot the values of K_2 as a function of time until steady conditions are reached.

8) Using arbitrary values of m, where m is defined as $(K_h/K_v)^{0.5}$, calculate corresponding values of K_2/K_1 (Equation 8); plot the m and K_2/K_1 values.

9) Determine actual K_2/K_1 (Equations 6 and 7).

10) Using the K_2/K_1 value determined in Step 9 above, find the corresponding value of m from the graph of K_2/K_1 versus m generated in Step 8.

11) Determine K_h (Equation 9).

12) Determine K_v (Equation 10).

Calculations--Equations for Stage I K_1 determination are as follows (Daniel 1987):

$$K_1 = \frac{d^2}{11\ D\ (t_2 - t_1)} \ln\ (H_1/H_2) \qquad (6)$$

where d = diameter of standpipe, m
t_1= initial time, s
t_2= final time, s
H_1= initial water level in standpipe, m
H_2= final water level in standpipe, m
D = diameter of borehole, m
K_1= hydraulic conductivity value for Stage I test, m/s

Equations for Stage II K_2 determination are as follows (Daniel 1987):

$$K_2 = A\ B\ \ln(H_1/H_2) \qquad (7)$$

$$A = \frac{d^2\ \ln[L/D + (1 + (L/D)^2)^{0.5}]}{8D\ [L/D]\ (t_2 - t_1)}$$

and

$$B = 1/[1 - 0.562e^{-1.57(L/D)}]$$

where t_1 = initial time, s
t_2 = final time, s
H_1 = initial water level in standpipe, m
H_2 = final water level in standpipe, m
D = diameter of borehole, m
K_1 = hydraulic conductivity value for Stage I test, m/s
K_2 = hydraulic conductivity value for Stage II test, m/s
L = length of extended hole, m

Equations for determining K_2/K_1 and m are as follows (Daniel 1987):

$$K_2/K_1 = m \frac{\ln[L/D + (1 + (L/D)^2)^{0.5}]}{\ln[mL/D + (1 + (mL/D)^2)^{0.5}]} \quad (8)$$

where L = length of extended hole, m
D = diameter of hole, m
K_1 and K_2 are given in Equations 7 and 8
m = constant

Equations for determining horizontal and vertical hydraulic conductivity (K_h) and (K_v) are as follows:

$$K_h = mK_1 \quad (9)$$

$$K_v = K_1/m \quad (10)$$

where K_h = horizontal hydraulic conductivity, m/s
K_v = vertical hydraulic conductivity, m/s
m = constant derived from Equation 9

Quality Assurance--A homogeneous soil is assumed to be permeated in Stages I and II of the Boutwell method. Tests performed in heterogeneous soil may give erroneous hydraulic conductivity values. A Boutwell permeameter test should, therefore, be performed on sections of the liner that are far removed from the boundaries. Tests conducted close to the edges of the liner can be affected by the boundary conditions and may, therefore, produce values that are not representative of the overall liner.

It is also necessary to assure saturated soil conditions around the vicinity of the borehole. This saturated condition may increase smearing of the soil surface in the borehole, especially during the Stage II test. Maximum effort should be made to minimize smearing of the soil surface during the Stage II tests.

Example Data--

Boutwell and Donald (1982) used a Boutwell permeameter to determine the field hydraulic conductivity of a natural clay and compared the values

with those determined in the laboratory on Shelby tube samples in a constant-head permeameter. The average laboratory hydraulic conductivity value was 7.2×10^{-10} m/s. Values from the field tests were found to be six times higher than the laboratory values. The authors explained that the difference was due to the jointed structure of this clay soil.

Boutwell and Derrick (1986) determined the field hydraulic conductivity of soils at two sanitary landfills. The horizontal conductivities of the stiff clay (CH) at the two sites were 1×10^{-10} and 3×10^{-10} m/s, whereas the respective vertical conductivities were 8×10^{-10} and 6×10^{-10} m/s.

Comments--

Boutwell permeameters can measure hydraulic conductivities of 1×10^{-9} m/s and less. The volume of soil tested in a single borehole, however, is relatively small. Because of the small size of the test area, soil macropores and other flaws in soil liner construction may be missed when this method is used. As a result, hydraulic conductivity determined by this method may not be representative of the actual field value.

Multiple tests could be conducted to evaluate a larger aggregate area. For several reasons, however, running many small tests may not achieve the desired test objective of obtaining a representative measure of the field hydraulic conductivity. For example, even if many tests were conducted, the small scale of each individual test would greatly increase the probability that through-going macropores (Anderson et al. 1985) would be truncated. Such truncation of through-going macropores would significantly reduce the hydraulic conductivity from the actual field value. Other problems include the large amount of potential smearing per unit volume of soil and the difficulty that may be encountered in distinguishing between defective test results and results reflecting the value of a small area of the soil liner with a nontruncated macropore.

The Boutwell method is a relatively fast means of determining soil hydraulic conductivity. It is also inexpensive, simple, and convenient to use; however, interpretation of results is open to some question. The effects of incomplete and variable saturation are unknown. The short test periods do not allow entrapped air to dissolve, and the method does not account for the effects of soil suction.

POROUS PROBES

These permeameters typically consist of a cone-shaped porous probe that is either pushed or driven into the soil (Daniel 1987). These probes can be used in a falling-head or a constant-head mode to determine hydraulic conductivity. One such commercially available porous probe that has been used to measure the hydraulic conductivity of soil liners is called the BAT permeameter. This device uses a falling-head method.

Principles

The BAT permeameter uses a falling-head method to determine hydraulic conductivity according to Darcy's law. A pressure transducer is used to measure the gas pressure in an evacuated or partially filled and pressurized test container. The container is temporarily connected to a porous probe that is installed in the soil. When fluid flows out of the container into the soil pores, a pressure change occurs and is recorded. The rate of pressure change is a direct function of the hydraulic conductivity of soil.

Methods

Apparatus--

Figure 5 depicts the major features of the BAT permeameter. These major features are as follows:

1) A porous probe to provide a hydraulic connection with soil pores.

2) A flexible septum that seals the upper end of the porous probe.

3) Test adapter.

4) Hypodermic needle.

5) Extension pipe.

Procedures--

The following is a listing of the procedures required in the use of a BAT permeameter:

1) Auger a hole 0.03 m (1 inch) in diameter to the desired depth.

2) Push the porous probe under static load into the augured hole.

3) Connect test adapters to the septum. (The hypodermic needle will pierce the septum as soon as this connection is made; the liquid in the container will then flow to the porous probe.)

4) Record the initial pressure from the pressure transducer and the initial volume of water in the test container.

5) Record the average pressure between times t_1 and t_2.

6) Measure and record the net pressure applied during the test.

7) Lift adapter off the tip to stop flow and to end test. The test container will instantly reseal to maintain the pressure in the test container.

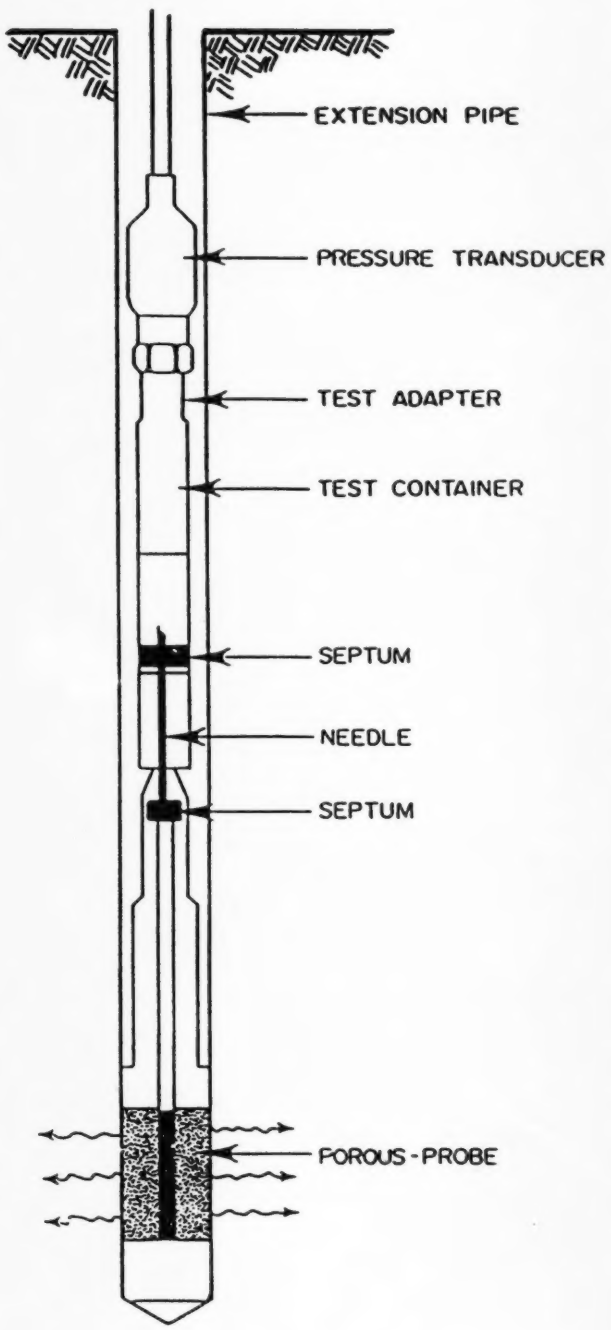


FIGURE 5. BAT PERMEABILITY SYSTEM (PETSONK 1985).

Calculations--

Petsonk (1985) discussed some of the calculations used to determine hydraulic conductivity with the BAT permeameter. The equations most often used with this method are as follows:

$$K = \frac{P_o V_o}{F} \quad \frac{1}{(P_t)^2 P_3} \quad \frac{\Delta P_t}{\Delta t} \tag{11}$$

where K = hydraulic conductivity, m/s
P_o = initial gas pressure in test container, m of water
V_o = initial volume of gas in test container, m^3
P_t = average measured pressure between times t-1 and t, m of water
P_3 = net pressure applied in test container, m of water
$\Delta P_t/\Delta t$ = rate of pressure change, m of water/s
A = cross-sectional area of flow, m^2
L = horizontal component of hydraulic conductivity gradient
F = flow factor, m

$$F = \frac{2 \pi y}{\ln[(y/d) + (1 + (y/d)^2)^{0.5}]} \tag{12}$$

y = length of porous probe, m
d = diameter of porous probe, m

Quality Assurance--

Sections of soil being tested may be disturbed and smeared during installation of the BAT permeameter. Minimum soil disturbance and removal of any smeared layer from the augured hole are critical to obtaining meaningful data by this method. Attention should be given to the probe installation procedure to minimize soil disturbance while obtaining a tight seal around the probes.

Petsonk (1984) and Torstensson (1984) noted that reproducibility of data from BAT tests is good. Torstensson (1984) showed the average hydraulic conductivity for a soft clay soil to be 1.5 ($\pm$ 0.07) x 10^{-10} m/s. The method was shown to be useful as a quality control tool in the field when quick relative hydraulic conductivity values are needed.

Example Data

Petsonk (1985) presented summary data gathered at Karlstad, Sweden (Petsonk 1984) for five soil types at different depths. The average conductivities of silty clay and clay soils were reported as 2.7 x 10^{-10} and 3.6 x 10^{-10} m/s, respectively. Variance for the soils was reported to be 23 and 35 percent, respectively. Field and laboratory hydraulic conductivity data for a California clay soil at depths of 0.18 and 0.45 m were also presented by Petsonk (1985). These data (Table 5) showed that values obtained with a BAT permeameter were one order of magnitude higher than those obtained in the laboratory with a triaxial permeameter.

Average hydraulic conductivity values from field tests on a compacted soil liner in a test fill were presented by Petsonk et al. (1987). The arithmetic mean conductivity values were 8.0×10^{-10} ($\pm$ 7.5) $\times 10^{-10}$ m/s for BAT and 6.5×10^{-10} m/s for SDRI (sealed double-ring infiltrometer). Figure 6 shows a plot of the hydraulic conductivity and pressure readings obtained with the BAT permeameter.

TABLE 5. FIELD AND LABORATORY MEASUREMENTS OF SATURATED HYDRAULIC CONDUCTIVITY IN A CALIFORNIA CLAY

Depth, m	BAT permeameter, m/s	Triaxial permeameter, m/s
0.18	3.7×10^{-10}	4.9×10^{-11}
0.45	4.4×10^{-10}	6.3×10^{-11}

[a] Source: Petsonk 1985

Hsien and Yamamoto (1987) determined field and laboratory hydraulic conductivity on a test fill liner 36 m x 24 m x 0.76 m. The data indicated the SDRI and BAT permeameter results were as much as two orders of magnitude higher than the laboratory determined values. Laboratory tests were performed on relatively undisturbed samples collected in Shelby tubes and tested in a triaxial permeameter. Hydraulic conductivity values determined by the BAT permeameter ranged from 6.2×10^{-12} to 1.9×10^{-9} m/s, whereas the SDRI indicated the hydraulic conductivity was at 2.7×10^{-9} m/s. The laboratory-determined hydraulic conductivities ranged from 1×10^{-11} to 2×10^{-11} m/s at a confining stress of 172 kPa. Whereas the triaxial permeameter yielded consistently low values, the BAT permeameter yielded values ranging from lower than the triaxial permeameter to higher than the SDRI.

Comments

Because the volume of soil tested by the BAT permeameter is small, the method is unlikely to yield values that are consistently representative of the overall hydraulic conductivity of the soil being tested. The BAT permeameter can measure hydraulic conductivities of 1×10^{-9} m/s or less; however, it primarily measures horizontal hydraulic conductivity. This makes interpretation of results for a soil liner at a RCRA-regulated facility difficult.

This device provides a simple and inexpensive method of measuring field hydraulic conductivity that requires minimum time and experience. Because it is a closed system, errors due to evaporation losses are eliminated.

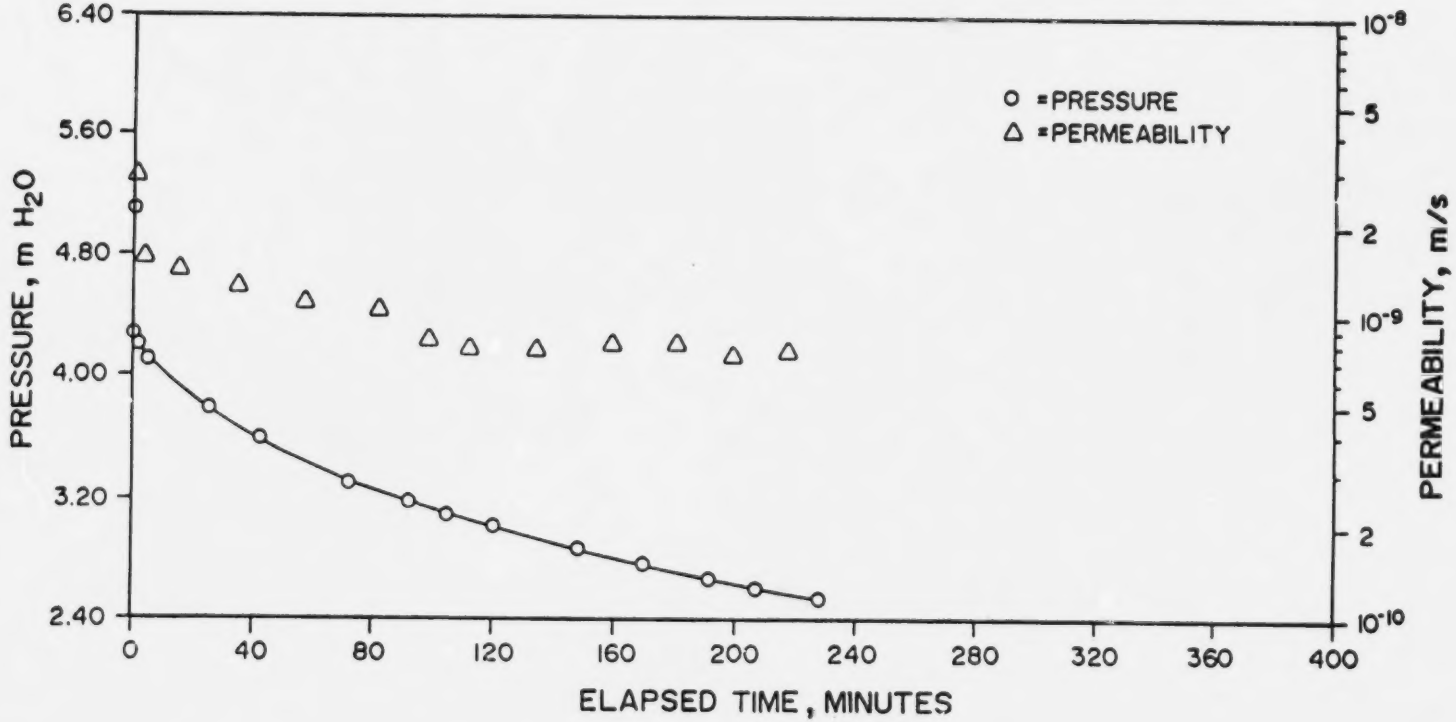


FIGURE 6. FIELD HYDRAULIC CONDUCTIVITY OF A SOIL LINER OBTAINED USING A BAT PERMEAMETER (PETSONK et al., 1987).

SURFACE INFILTRATION DEVICES

Included in this section are all field hydraulic conductivity methods that measure the rate water enters a soil liner. These methods include single- and double-ring infiltrometers of various designs. A method for converting from infiltration rate to hydraulic conductivity is given in the section on the modified double-ring infiltrometer. With all surface infiltration methods, care should be taken to protect the soil surface from desiccation.

ASTM Double-Ring Infiltrometer

In ASTM Method D 3385, double-ring cylinders are used to determine the rate of infiltration of water into soils. For more than a decade, this method has been used widely for the evaluation of both percolation rate in septic fields and infiltration rate in soils to be irrigated. Two open cylinders, one inside the other, are driven into the soil and partially filled with water. A constant water level is maintained on the soil by continuously adding water to the soil in the rings. The volume of water added in a given period is used to determine the rate of infiltration.

Principle--

The reasoning behind the double-ring method was to let the outer annular space between the two rings serves as a buffer area in which the lateral flow would be diminished. This would allow the measurement of only vertical infiltration from the inner ring. The test can be used at the soil surface or at a given depth in pits, as long as the test surface is above the water table.

Method--

This method is documented in the 1988 Annual Book of ASTM Standards, Section 4, Volume 4.08, and the reader is referred to ASTM Standard No. D 3385-88 for details of the procedures and calculations. (The ASTM standards are updated annually, and the most recent edition should be obtained.)

Apparatus--Figure 7 is an illustration of an ASTM double-ring infiltrometer. The following list summarizes the equipment needed for the ASTM method to determine the rate of infiltration of water into a soil:

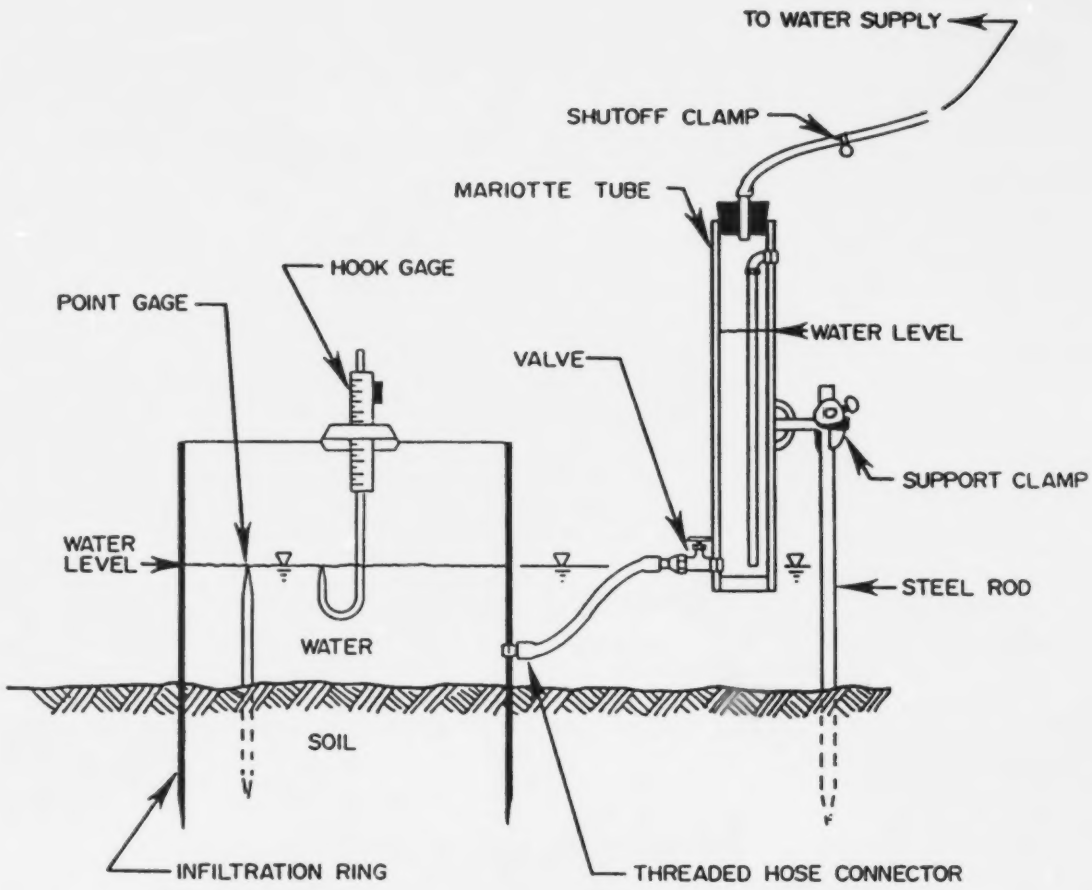
1) Two cylinders 30 and 60 cm in diameter and 50 cm in height, constructed of 1/8-inch steel beveled at the bottom.

2) One 200-liter (55-gallon) barrel for water supply to outer ring.

3) One 1000-ml graduated Mariotte tube for measurement of the water flow to the inner ring during the test.

4) Wooden block and sledge hammer.

5) Aluminum disks 1.3 cm thick with diameters slightly larger than the infiltrometer rings.



NOTE: Outer ring has been eliminated for simplification of the illustration.

FIGURE 7. ASTM DOUBLE-RING INFILTROMETER (MODIFIED FROM ASTM 1988).

6) Hook gauge, steel tape, or rule for use in controlling and measuring depth of water in the infiltrometer ring.

Procedure--Details of the procedure are in the 1988 Annual Book of ASTM Standards, Section 4, Volume 4.08 (Standard No. D 3385).

Calculations--Calculations involve converting the volume of liquid used during each time interval into an incremental infiltration rate for both the inner and outer ring by use of Equations 13 and 14:

Inner Ring:

$$I_{IR} = V_{IR}/(A_{IR} \times t) \quad (13)$$

where I_{IR} = infiltration rate of soil in inner ring, cm/h
V_{IR} = volume of liquid used during time interval to maintain constant head in inner ring, cm^3
A_{IR} = inner ring soil surface area, cm^2
t = time interval, h

Outer Ring:

$$I_{OR} = V_{OR}/(A_{OR} \times t) \quad (14)$$

where I_{OR} = Infiltration rate of soil in outer ring, cm/h
V_{OR} = Volume of liquid used during time interval to maintain constant head in outer ring, cm^3
A_{OR} = Outer ring soil surface area, cm^2
t = time interval, h

Quality Assurance--Driving in the rings with a sledgehammer can fracture a test soil that is dry or stiff and lead to false high values. In addition, the test rings should be protected from the environment, animals, and vandalism. Intercepted rainfall or high evaporative losses may also lead to false values.

Example Data--

Bagchi (1986) presented data for comparison of laboratory and field properties of blended soil in a landfill in Wisconsin. Average laboratory and double-ring hydraulic conductivities of 6.0×10^{-10} and 2.0×10^{-6} m/s were reported.

Comments--

This equipment should not be used to measure infiltration rates on compacted soil liners. According to ASTM (1988), this method may be both difficult to use and unreliable in soils with a hydraulic conductivity less than about 1×10^{-8} m/s. Also, loss of water due to evaporation may be higher than the quantity of water permeating the soil.

The surface area of the inner ring of the ASTM double-ring infiltrometer is larger than most laboratory permeameters, but smaller than several types of currently available field infiltrometers. No definitive

data base exists that conclusively indicates the minimum infiltrometer size necessary for consistently yielding infiltration rates equivalent to that of the overall soil liner. A substantial body of information suggests that the larger infiltrometers (>2 m^2) do give a reliable indication of field performance (Elsbury et al. 1988). Consequently, equipment such as the ASTM double-ring infiltrometer, which evaluates relatively small areas, should not be used to test materials, such as soil liners, that may have widely spaced macropores. Although these widely spaced macropores may represent only a small fraction of the total porosity of the soil liner, they also may serve as the conduits for most of the flow through the liner.

Rings used in this method can be driven into the soil with a sledgehammer, a heavy bulldozer blade, or other equipment. Caution should be exercised when driving the rings into especially stiff or dry soil because the soil may fracture, which can result in artificially high hydraulic conductivities.

As with many field infiltrometers, hydraulic conductivity cannot be directly determined with this device unless all boundary conditions are known (e.g., the hydraulic gradient and the extent of lateral flow).

Modified Double-Ring Infiltrometers

Modifications have been made to the basic ASTM double-ring infiltrometer to make it more sensitive for measuring low infiltration rates. These modifications include the use of a large outer ring and sensitive water level measuring devices.

Principles--

The principles behind this method are similar to those presented earlier for the ASTM double-ring infiltrometers. The primary difference is that the outer ring has been enlarged for further minimization of the potential for a lateral flow component in the infiltration rate measured with the inner ring. Other differences from the ASTM double-ring method are designed to increase the ability of the equipment to measure infiltration rates less than 1×10^{-8} m/s.

Method--

The method is similar to that for the ASTM double-ring infiltrometer except for its use of a larger outer ring, sensitive water level measuring devices, and the installation of tensiometers in the ring to measure soil moisture tension at various soil depths. The sensitivity of the system may be increased further by preventing evaporative loss of water (i.e., covering the infiltrometers with suitable material that acts as a moisture barrier).

Apparatus--Figure 8 shows a modified double-ring infiltrometer that uses larger rings, float valves to maintain a constant water level in the rings, and level recorders. The main components of the system are as follows:

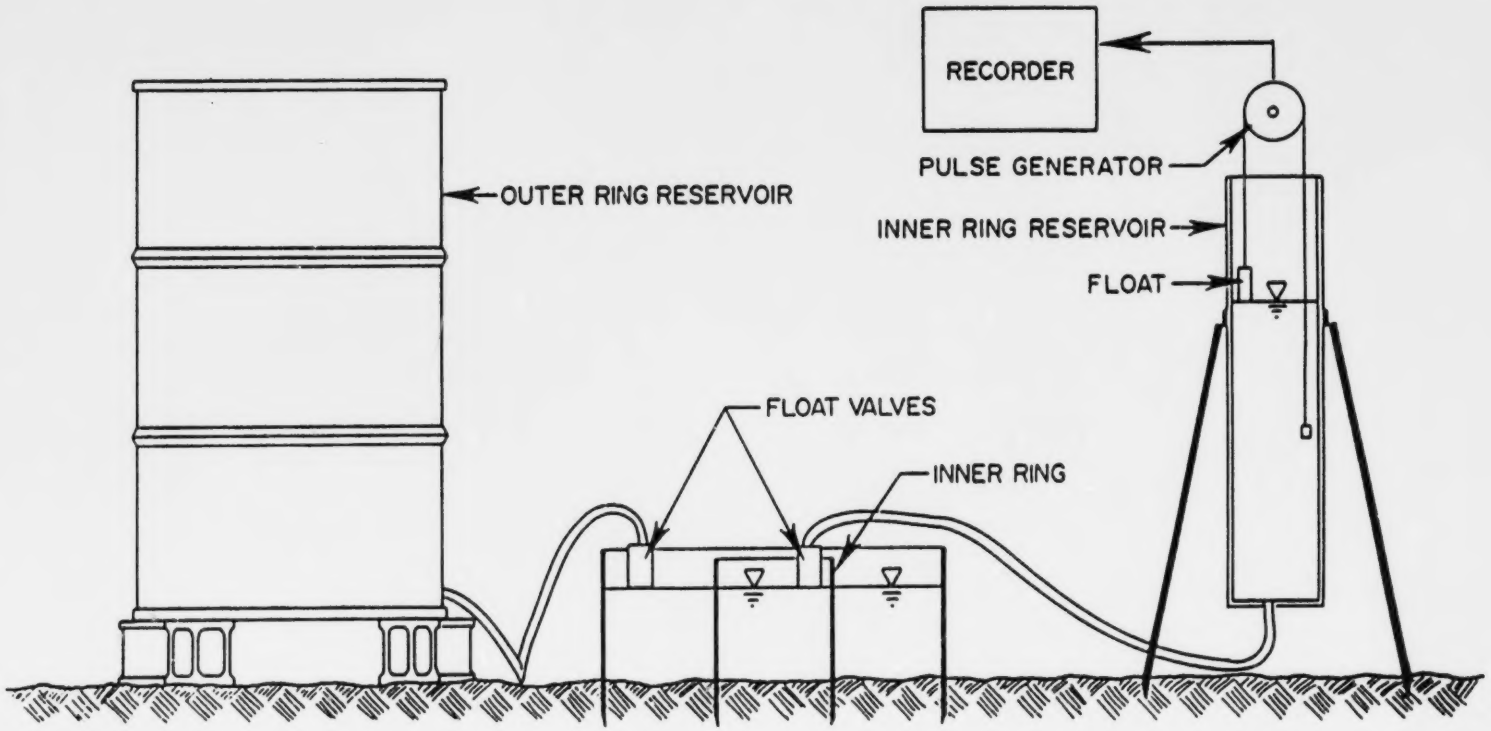


FIGURE 8. MODIFIED DOUBLE-RING INFILTROMETER WITH A LEVEL RECORDER (BROWN 1985).

1) Two cylinders 30 and 76 cm in diameter and 30 cm high, constructed of 1/8-inch steel.

2) Supply tube to inner ring made of 15-cm-diameter steel tubing.

3) A 55-gallon barrel to supply water to the outer ring.

4) Adjustable float valves.

5) Level recorder.

6) Wooden block, sledgehammer, and carpenters level.

Figure 9 shows an ASTM double-ring infiltrometer setup modified to include the use of tensiometers. Procedures for this device are similar to those given in Section 4, except that a constant water level is not required. Changes in water level in the rings are periodically measured with a hook gauge.

Procedure--The following is a listing of the procedures used in this modified double-ring infiltrometer:

1) Drive steel rings (inner and outer) into soil as in the ASTM double-ring infiltrometer method.

2) Connect float valves to the inner and outer ring; adjust the level of the floats to maintain a water level of 10 to 15 cm in the rings.

3) Use a pail to fill both rings with liquid to the same desired depth, making sure to prevent scouring of the soil surface by using a splash guard.

4) Connect inner and outer rings to their respective water supply tubes.

5) Cover the rings with a sheet of plastic or suitable material to prevent evaporation from the liquid surface.

6) Cover the open end of the supply tube to prevent evaporation of water from the tube.

7) Periodically record the liquid level in the rings with a level recorder mounted on top of the supply tube.

Calculations--The volume of water used during each measured time interval is converted into an incremental infiltration rate by the following equations:

$$I = (d^2 \times h)/(D^2 \times T) \qquad (15)$$

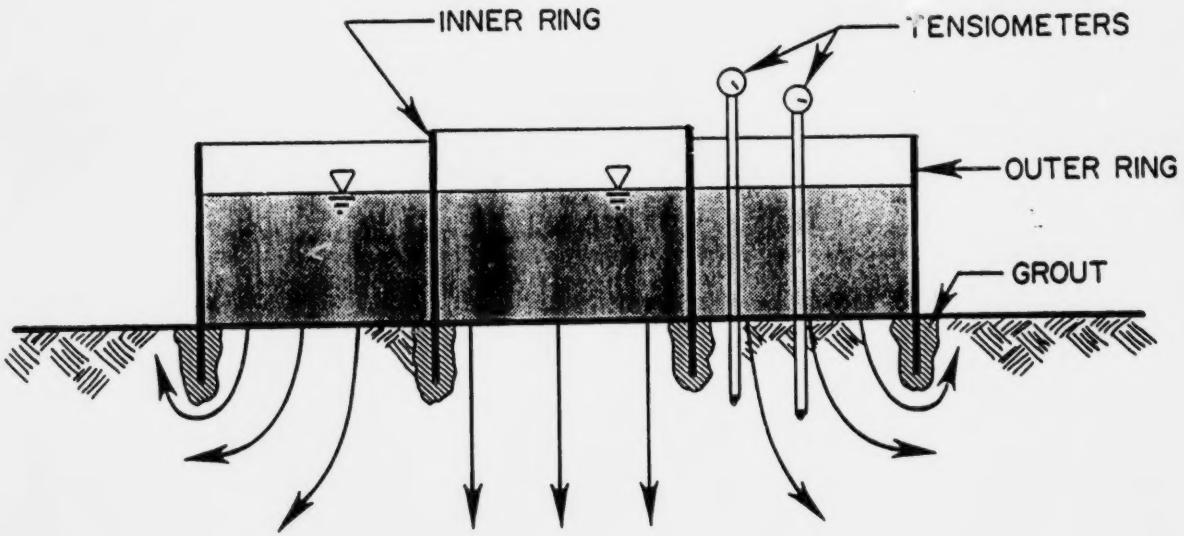


FIGURE 9. ASTM DOUBLE-RING INFILTROMETER WITH TENSIOMETER.

where I = infiltration rate, m/s
d = diameter of liquid supply tube, m
D = diameter of ring, m
h = liquid level drop in the supply tube, m
T = elapsed time between readings, s

The incremental infiltration rates are then plotted to show infiltration rate change with time. This curve will show an exponential decline in infiltration rate with time. If the test is run to the point where the soil is at or near saturation (i.e., steady-state), the curve will be practically flat, which indicates a constant infiltration rate with time. If the depth to the wetting front is known, the hydraulic conductivity can be calculated from the infiltration rate as follows:

$$K = I/H \tag{16}$$

where K = hydraulic conductivity, m/s
H = hydraulic gradient = (h + L)/L
h = depth of water in the inner ring, m
L = depth to wetting front, m
I = infiltration rate, m/s

Equation 17 is used to calculate the infiltration rate of the soil when tensiometers are used with the double-ring infiltrometer, as shown in Figure 9.

$$I = k[1 + (D_f/L_f) + (U/L_f)] \tag{17}$$

where I = infiltration rate, m/s
k = hydraulic conductivity, m/s
D_f = depth of liquid above soil surface, m
L_f = depth of wetting front, m
U = soil moisture tension at the wetting front, m

Tensiometer readings are recorded during the hook gauge measurement period and used to determine the depth of the wetting front in the rings. The test is analyzed by plotting infiltration rate with time. The wetting front is determined when the tensiometer at that depth registers zero soil moisture tension.

Quality Assurance--Quality assurance considerations for this method are similar to those given in the section on ASTM double-ring infiltrometers. Care should be taken to calibrate all level recording devices and to install tensiometers such that leakage along the bored hole does not occur.

Example Data--

Rogowski et al. (1984) used a modified double-ring infiltrometer (barrel infiltration ring) to determine the hydraulic conductivity of a compacted soil liner. The outer ring was 0.6 m in diameter and the inner

ring was 0.3 m. Figure 10 shows the inner ring infiltration rate as a function of time. The steady-state infiltration rate was approximately 1×10^{-9} m/s.

A modified double-ring infiltrometer similar to that shown in Figure 8 was used to determine the infiltration rate of two clay soils at sites in Austin, Texas (Brown 1985). The saturated infiltration rates of the two clay soils were 6.7×10^{-8} and 1.3×10^{-7} m/s.

Comments--

With modifications similar to those shown in Figure 8, the ASTM double-ring infiltrometer has been used to measure infiltration rates of $9.7 (\pm 8.1) \times 10^{-10}$ m/s (Rogowski et al. 1985). The ability of the test to obtain representative values is questionable, however, because of the relatively small size of the the inner ring (0.3 m in diameter). Macropores that can affect the infiltration rate by orders of magnitude could have a wider average spacing than the diameter of the inner ring.

Box Infiltrometer

This method involves the use of a sealed box and a relatively complex standpipe arrangement to measure infiltration into soil in a 0.36-m^2 area. It has been used to measure hydraulic conductivities as low as 5×10^{-10} m/s.

Principles--

Box infiltrometers work on the same principles as the ASTM double-ring infiltrometer (ASTM D-3385). This method, however, differs from the ASTM D-3385 method by eliminating evaporative losses through the use of a sealed inner ring (Anderson et al. 1984). A float valve and a thermal expansion reservoir assembly are used to maintain a constant head on the soil in the 0.6-m x 0.6-m domed stainless steel box. Diurnal changes occur in the volume of water in the infiltrometer as the result of ambient air temperature changes. These water volume changes are accommodated in the thermal expansion reservoir placed around the float valve chamber. Evaporative losses are eliminated by completely sealing the refill reservoir (standpipe) except for a small vent at the top for maintaining atmospheric pressure in the reservoir. Changes in water level in the refill reservoir are used to estimate the infiltration rate of the soil under the sealed domed box.

Method--

Apparatus--Figure 11 is an illustration of an installed box infiltrometer. Its main features are as follows:

1) Stainless steel domed box.

2) Refill reservoir.

3) Thermal expansion reservoir and float valve assembly.

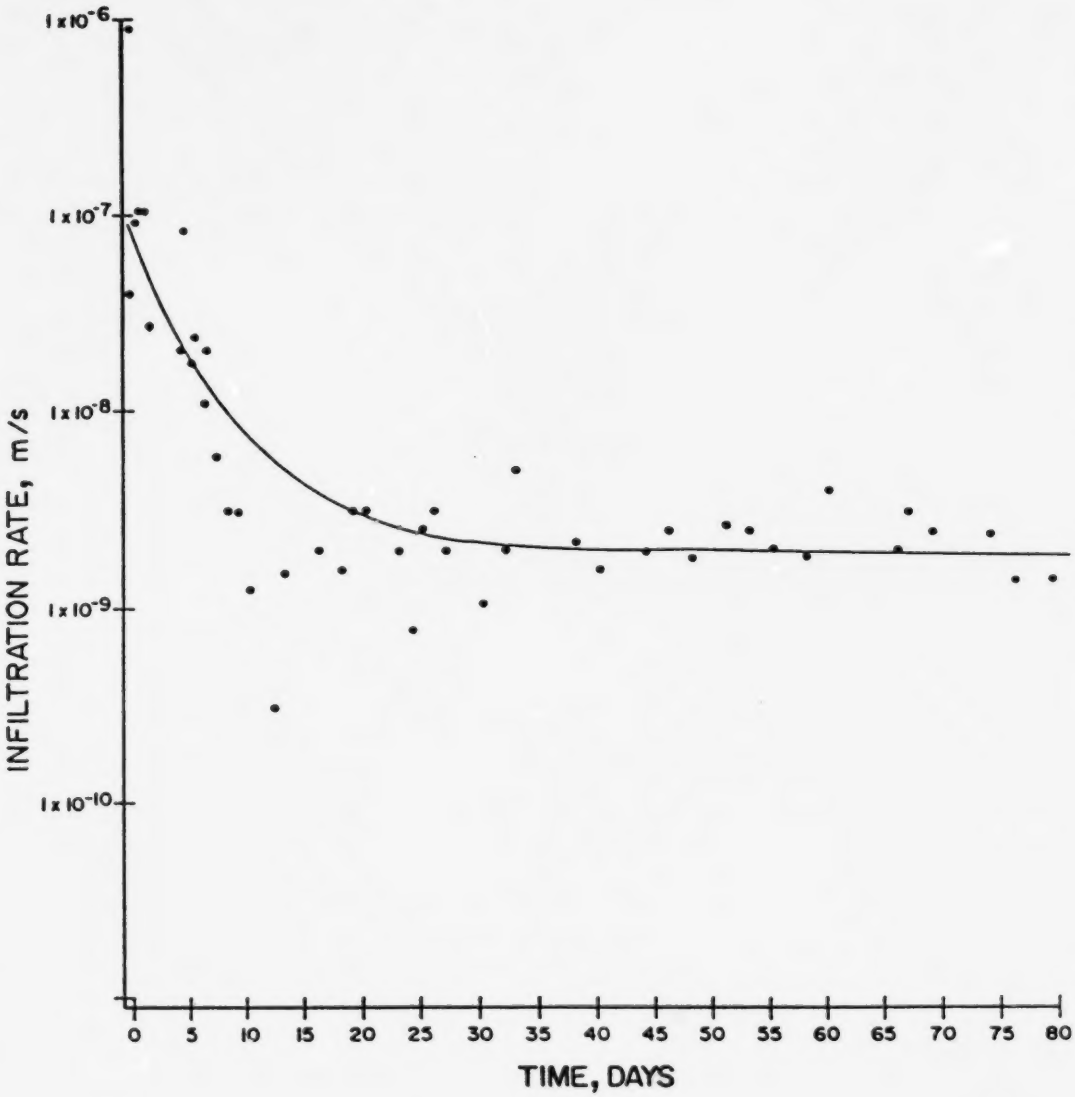


FIGURE 10. INFILTRATION RATE PLOTTED AS A FUNCTION OF TIME, USING DATA FROM THE INNER RING OF A DOUBLE-RING INFILTROMETER (ROGOWSKI et al. 1984).

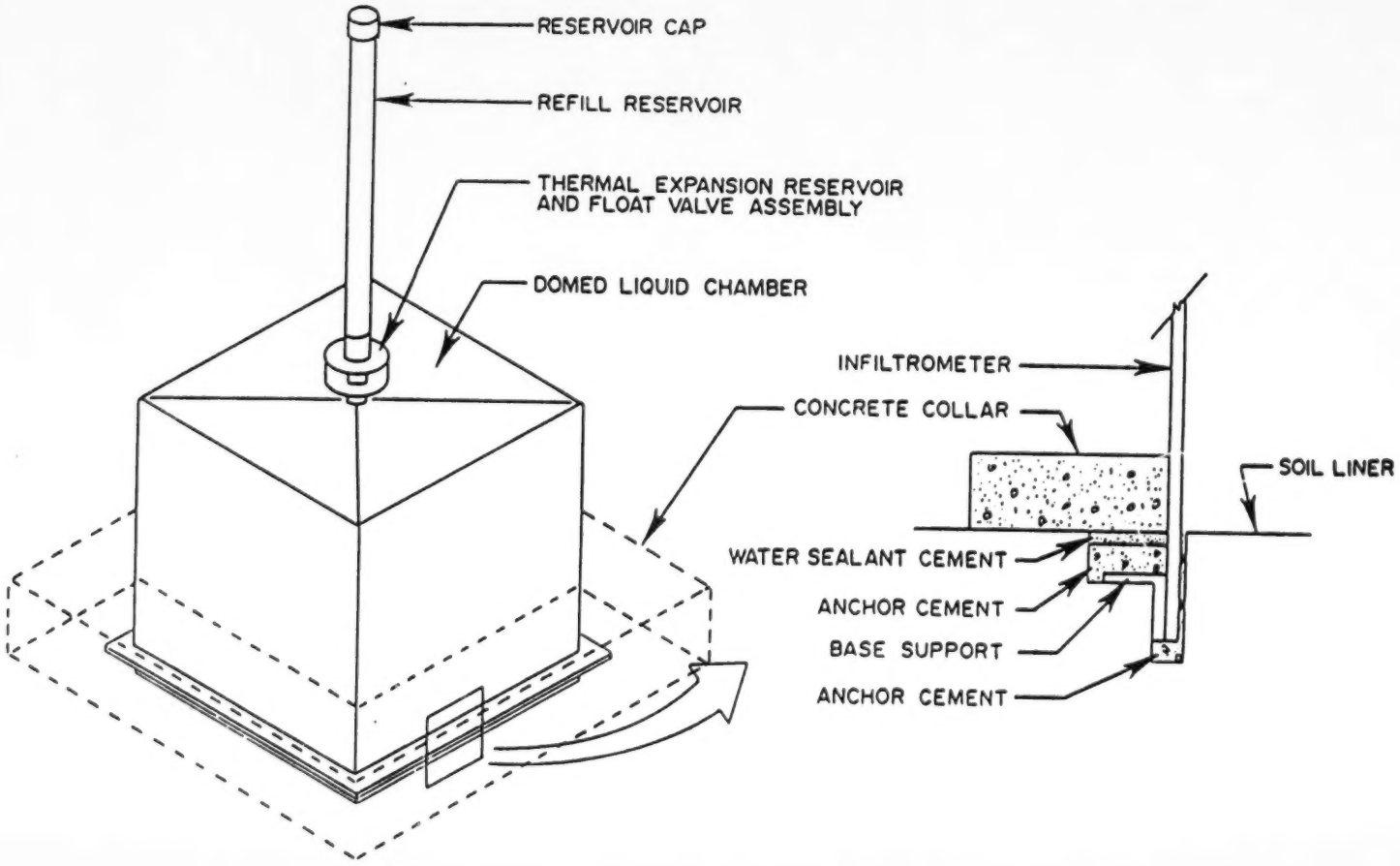


FIGURE II. BOX INFILTROMETER WITH DETAIL OF EMBEDDED BASE SUPPORT (ANDERSON et al. 1984).

Procedure--The following is a listing of the procedures used with an installed box infiltrometer:

1) Dig the outer ring trench (1.5 m diameter).

2) Dig a trench on a level 0.6-m by 0.6-m surface of the soil liner inside the outer ring trench.

3) Fill the inner ring trench with anchor cement to approximately three-fourths of the trench depth and immediately lower the domed steel box into the trench.

4) Fill the outer ring trench with anchor cement to about three-fourths of the trench depth and immediately lower the outer ring into the trench.

5) Allow the cement to cure for 45 minutes.

6) Fill the steel box with liquid to a depth of about 15 cm and check for leaks between the box and the soil.

7) Fill the outer ring until the domed steel box is covered with liquid; allow the box to fill with liquid.

8) Attach the float valve and thermal expansion reservoir.

9) Attach refill reservoir.

10) Fill the refill reservoir with liquid and attach the cap.

11) Periodically measure the level of liquid in the refill reservoir and the temperature of the water in the outer ring.

Calculations--The following form of Darcy's equation is used to calculate the hydraulic conductivity of the soil liner:

$$K = V/(ATH) \tag{18}$$

where V = volume of liquid that flowed from the refill reservoir, m^3
A = cross-sectional area over which infiltration occurred, m^2
T = time in which liquid volume was measured, s
H = hydraulic gradient = $(h + L)/L$
h = depth of water in steel domed box, m
L = soil liner thickness, m

Equation 19 is used to determine the liquid volume change due to thermal expansion of liquid and steel:

$$dV = V_o \, dT \, (B_w - B_s) \tag{19}$$

where dV = change in liquid volume due to temperature change, m^3
V_o = volume of liquid at measured temperature, m^3

dT = change in temperature, ^{o}C
B_w = coefficient of volume expansion of liquid, $1/^{o}C$
B_s = coefficient of volume expansion of steel, $1/^{o}C$

Quality Assurance--The quality of the data from this test depends on obtaining all data on concurrent tests at the same time during the day to offset the fluctuation in water level measurements due to differential thermal expansion of water and steel. The temperature of the liquid should be recorded and used to adjust the measured volume of liquid to that at a specified temperature (Equation 19). Data from this test should be plotted to determine when the infiltration rate of the soil has reached a steady state.

A trench and anchor cement should be used to install the box into the soil liner to control leakage of liquid around the bottom of the infiltrometer sidewalls. The infiltrometer also must be insulated from heat to minimize temperature changes in water and the steel material used to construct the box.

Example Data--

Anderson et al. (1984) used box infiltrometers to evaluate hydraulic conductivity of a 0.13-m-thick soil liner. The liner was constructed of a mixture of 80 percent coarse sand and 20 percent bentonite. The mixture was compacted to greater than 100 percent maximum density as determined by ASTM Method D-698. Four box infiltrometers were used simultaneously on the soil liner to evaluate the variability of steady-state hydraulic conductivity values. The overall mean steady-state value for the infiltrometers was 4.2 ($\pm$ 1.2) x 10^{-10} m/s.

A small error is introduced into the measurements made with this device when a temperature change occurs. For each degree centigrade change in temperature, a change of approximately 0.04 m will occur in the depth of water initially in the infiltrometer.

Daily fluctuations occurred in the hydraulic conductivity values, but the trend in the fluctuations was the same for all four infiltrometers (Figure 12). This appears to indicate that the cause of daily variation was not measurement errors, but rather actual fluctuations in the infiltration rate with time.

Comments--

Box infiltrometers are capable of measuring hydraulic conductivity values substantially lower than 1 x 10^{-9} m/s. It is unlikely that a single box infiltrometer would cover sufficient area (0.36 m^2) to determine the overall field hydraulic conductivity. In the study by Anderson et al. (1984), however, the box infiltrometer was used in arrangements of four to allow definition of both the overall field hydraulic conductivity and the spatial variability of the liner. The number of infiltrometers used (four) appeared to be sufficient to define spatial variability. In addition, in the single study conducted, the aggregate area evaluated by the infiltrometers (1.44 m^2) appeared to be sufficient to obtain representative hydraulic conductivity values. It should be noted that the test site was

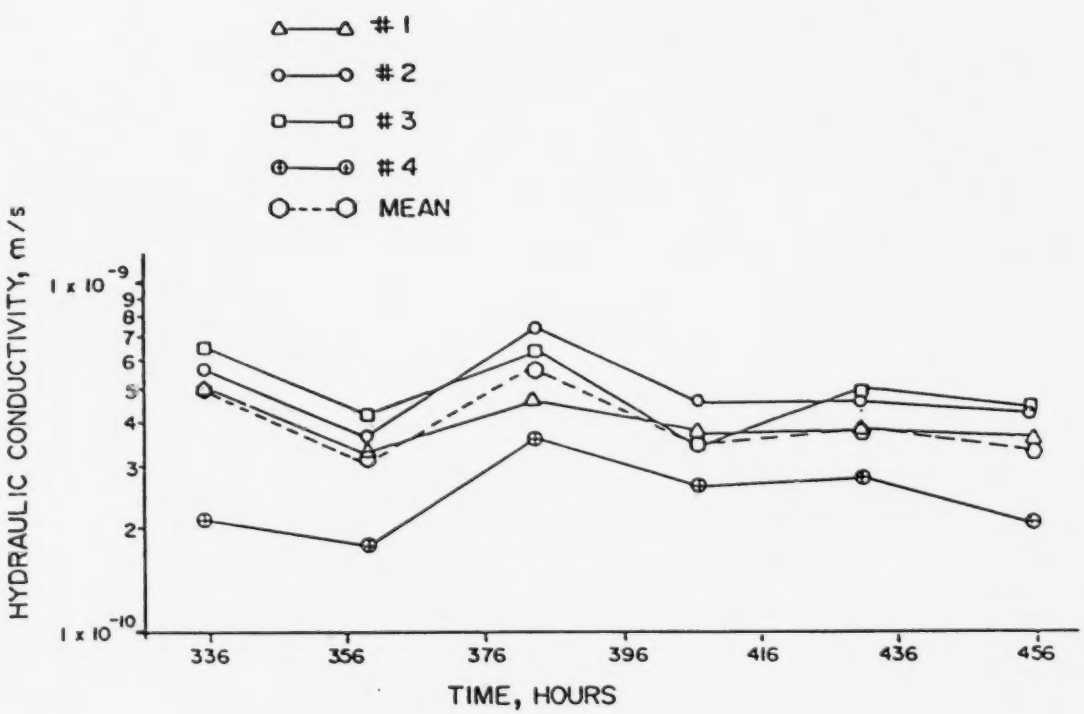


FIGURE 12. HYDRAULIC CONDUCTIVITY OF THE SAND-BENTONITE LINER MEASURED USING FOUR BOX INFILTROMETERS (ANDERSON et al. 1984).

small (8 m^2) and that it required a larger effort per unit area to produce a uniform soil liner than is typical for full-scale liners. Consequently, although an aggregate area of 1.44 m^2 was sufficient to characterize the spatial variability of the test site, it probably would be necessary to test a larger area under conditions more typical of full-scale liners.

The box infiltrometer is relatively difficult to use and would definitely require skilled personnel for installation, monitoring, data collection, and data analysis. Temperature fluctuations can greatly influence the apparent infiltration with this method. Consequently, data should be collected at the same time each day, and the values obtained should be adjusted to compensate for thermal expansion or contraction of the water and test equipment.

Single-Ring Infiltrometer

A single-ring infiltrometer consists of a metal cylinder 20 to 60 cm in diameter, which is pressed or driven into the soil. Infiltration is measured by ponding water inside the cylinder and by measuring the rate that the free surface falls, or by measuring the rate at which water must be added to maintain a constant depth in the cylinder (Day and Daniel 1985a). A network of tensiometers may be used to determine the depth of the wetting front, which is subsequently used to calculate the hydraulic conductivity of the soil.

Principles--

The single-ring method is similar to the double-ring method except for the elimination of the outer ring. When the wetting front exceeds the depth of the buried cylinder, water flows from the ring vertically and laterally. The lateral flow may cause the measured infiltration rate to be higher than expected, and a correction factor (Day 1984) can be used to account for the effect of lateral flows on the determined saturated hydraulic conductivity values.

Method--

Apparatus--A schematic diagram of a single-ring infiltrometer is shown in Figure 13. Essential features of the infiltrometer include the following:

1) Metal cylinders 20 to 60 cm in diameter.

2) A hook gauge or suitable method of maintaining constant water level in the cylinder.

3) Tensiometers.

4) Plastic sheeting to cover the ring.

Procedure--The following is a listing of the procedures used with single-ring infiltrometers:

1) Carefully install the single-ring cylinder into the soil liner.

2) Install hook gauge or Mariotte tube (or suitable method for maintaining constant water level).

3) Install tensiometers at different depths to monitor depth of the wetting front. (Typical depths are 0.15, 0.30, and 0.46 m.)

4) Add water to the ring, making sure not to scour the soil, and cover the inner ring with plastic sheeting.

5) Record time, volume of water used to maintain the constant head, and tensiometer reading.

Calculation--The constant-head equation (Equation 20) or the falling-head equation (Equation 21) can be used to calculate the saturated hydraulic conductivity of the soil.

$$K = Q\ L\ /(H\ A\ t) \tag{20}$$

or

$$K = \frac{L \ln(H_2/H_1)}{t} \tag{21}$$

where K = hydraulic conductivity, m/s
L = depth to wetting front, m
H = head loss through liner, m
A = cross-sectional area of soil in the ring, m^2
t = elapsed time between readings, s
Q = volume of water that infiltrated into the soil, m^3
H_1 = initial depth of water in cylinder, m
H_2 = depth of water in cylinder after time interval t, m

Quality Assurance--The value of the hydraulic conductivity obtained from the single-ring infiltrometer when Equations 20 or 21 are used is multiplied by a shape factor (F), which varies from 0 to 1 (Day 1984) to account for lateral spreading (Figure 14). The correction factor is based on the geometry of the soil liner, the infiltrometer, and the degree of anisotropy of the soil. Hydraulic conductivity versus time relationship should also be plotted to show a steady-state saturated hydraulic conductivity has been attained.

Example Data--

Stewart and Nolan (1987) reported hydraulic conductivity data on six soil liners as determined by 0.56-m single-ring infiltrometers. The hydraulic conductivities varied from 2.3×10^{-9} to 3.0×10^{-8} m/s. Laboratory hydraulic conductivity values from fixed-wall permeameters that used Shelby tube samples taken from the soil inside the infiltrometers after completion of infiltrometer tests ranged from 1.8×10^{-10} to 5.5×10^{-10} m/s.

Bagchi (1986) reported data on the permeability of blended soil used to construct a landfill soil liner. These data indicated field hydraulic conductivities determined with a 0.15-m diameter single-ring permeameter

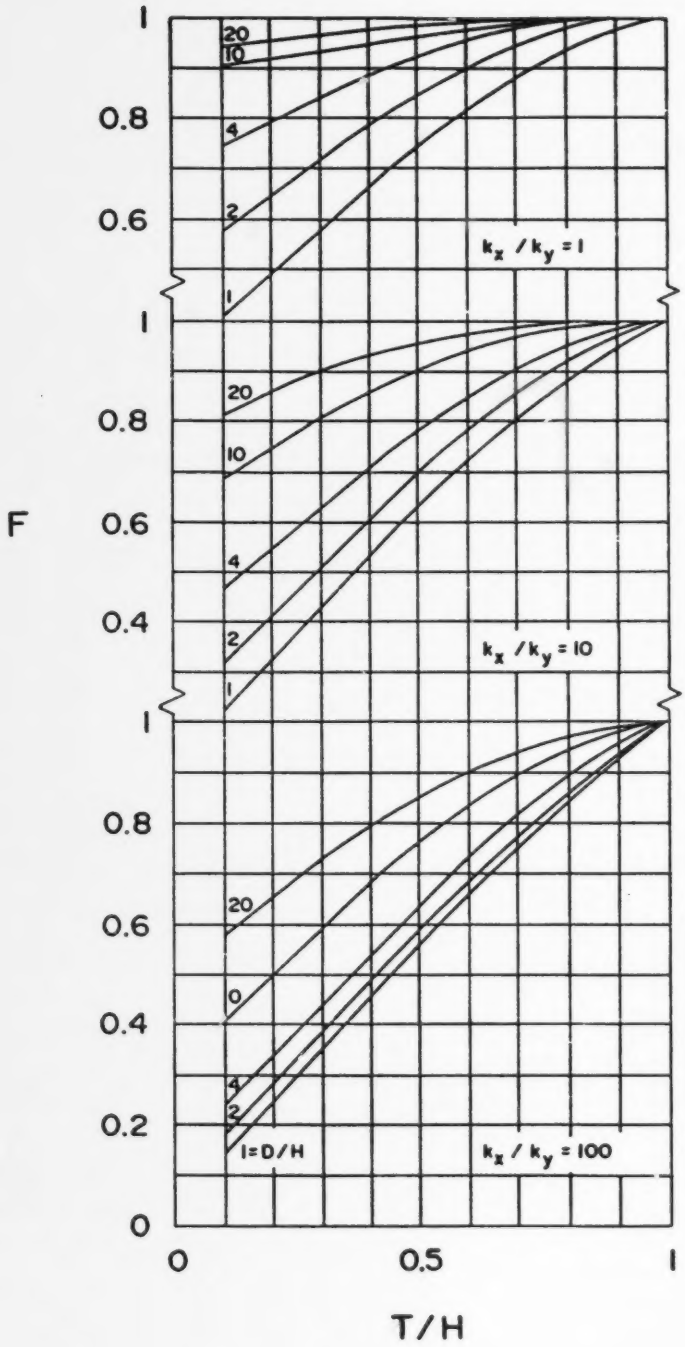


FIGURE 14. SHAPE FACTOR (F) FOR SINGLE-RING TEST (DAY 1984).

and a double-ring permeameter (0.15-m-diameter inner ring and 0.61-m-diameter outer ring) to be 4 x 10^{-7} and 6 x 10^{-7} m/s, respectively, compared with a laboratory permeability of 3 x 10^{-7} m/s.

Triad Engineering Consultants, Inc. (1986) used a 55-gallon open drum (0.6 m in diameter) as a single-ring infiltrometer to determine field hydraulic conductivity of a compacted clay liner in West Virginia. The overall hydraulic conductivity of the liner was determined to be 5.6 x 10^{-10} m/s. Average data from the three rings used are 8.0 x 10^{-10}, 2.8 x 10^{-10}, and 6.0 x 10^{-10} m/s, compared with the average laboratory value of 2.0 x 10^{-10} m/s.

Day and Daniel (1985b) determined the field hydraulic conductivity of two prototype clay liners by using single-ring and double-ring infiltrometers. Results are summarized in Table 6. The single- and double-ring data were within one order of magnitude.

TABLE 6. HYDRAULIC CONDUCTIVITY OF TWO PROTOTYPE CLAY LINERS USING A SINGLE-RING AND A DOUBLE-RING INFILTROMETER

Soil, m	Type of ring	Diameter of ring, m	Hydraulic conductivity, m/s
Clay 1	Single	0.56	7.2 x 10^{-7}
	Single	0.56	1.5 x 10^{-7}
	Single	1.22	1.2 x 10^{-8}
	Single	1.22	1.0 x 10^{-8}
	Double	0.30 and 0.51	1.8 x 10^{-8}
Clay 2	Single	0.56	1.0 x 10^{-8}
	Single	0.56	3.5 x 10^{-7}
	Single	0.56	3.4 x 10^{-8}
	Single	1.22	1.6 x 10^{-8}
	Double	0.30 and 0.51	2.5 x 10^{-8}

Golder Associates (1984) used two 3.1-m-diameter infiltration rings to determine the in situ hydraulic conductivity of a compacted fill in Georgia. Hydraulic conductivity values for both rings ranged from 4.3 x 10^{-10} to 1.5 x 10^{-9} m/s, with an average value of 7.8 x 10^{-10} m/s.

Comments--

Large single-ring infiltrometers can measure hydraulic conductivity values as low as 1 x 10^{-9} m/s. If the ring is of sufficient diameter, the hydraulic conductivity values obtained should be representative of the overall soil liner. Until there is a definitive data base documenting the minimum ring diameter needed to obtain these representative values, a total area of at least 2 m^2 within the ring is recommended.

Errors can be introduced into the hydraulic conductivity values as a result of lateral flow and evaporative losses. There is no danger of falsely concluding that a soil liner meets a specific performance standard, however, as long as the uncorrected hydraulic conductivity values are less than 1×10^{-9} m/s. If it is necessary to use a correction factor to reduce hydraulic conductivity below 1×10^{-9} m/s, additional tests should be conducted either with a double-ring infiltrometer or by using measures to eliminate evaporative losses.

Single-ring infiltrometers have the advantages of being simple and inexpensive. Care should be taken, however, to make sure that thermal expansion of the water does not yield false low values. Other possible sources of false low values are the interception of rainfall by the open ring or incorrect calculation of the hydraulic gradient. These sources of error can be avoided by using a sealed ring and a free drainage layer beneath the known thickness of a soil liner, respectively.

Sealed Double-Ring Infiltrometer

This method involves the use of a sealed ring or box that measures infiltration into a relatively large area. The sealed double-ring infiltrometer (SDRI) has a sealed inner ring that permits measurement of low infiltration rates and minimizes problems with temperature fluctuations and evaporation (Elsbury et al. 1988). It is relatively easy to operate, but as with all infiltration ring devices, it must be carefully installed to assure that no leakage occurs around the edges.

The sealed double-ring infiltrometer consists of an inner ring and an outer ring. The fiberglass inner ring is 1.5 m^2 in diameter and has a sloped top that extends only 12 cm above the liner surface. The outer ring, which is made of 3.7-m-long aluminum panels, is used to pond water around the inner ring to insure vertical percolation in the inner ring. Flow is measured during an infiltration test by using a flow-measurement bag attached to the infiltrometer through Tygon tubing. Any water flow out of the infiltrometer into the ground is replaced by water from the bag. Flow measurement is initiated by filling the bag with a known weight of water, connecting the bag to the infiltrometer, and periodically retrieving and reweighing the bag.

Principles--

An SDRI uses the double-ring infiltration principle to measure hydraulic conductivity of saturated soil near the ground surface. This consists of ponding water on the ground surface and measuring the amount of water that enters the soil in a given time interval. The double-ring arrangement is designed to assure that the flow from the inner ring is vertical. If the hydraulic gradient is known, the infiltration rate can be used to determine hydraulic conductivity with Equation 23.

Method--

Apparatus--A schematic of an SDRI is shown in Figure 15. The following are the essential features:

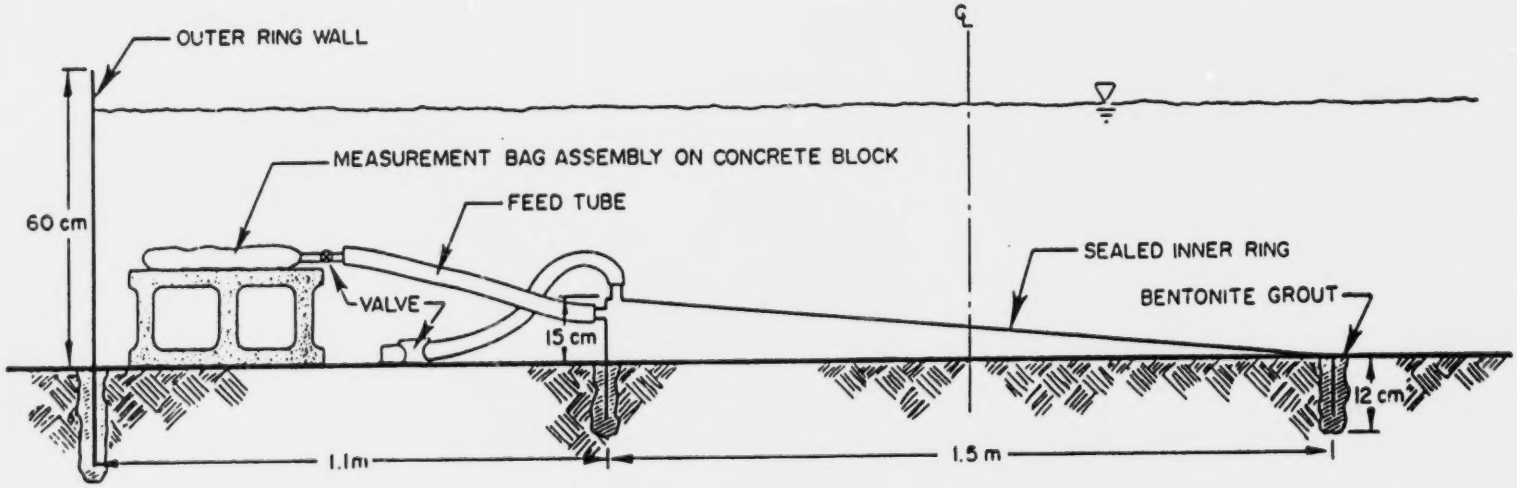


FIGURE 15. SCHEMATIC OF A SEALED DOUBLE-RING INFILTROMETER. (MODIFIED FROM ELSBURY et al. 1988).

1) A sealed fiberglass inner ring.

2) An open metallic outer ring.

3) Flow-measurement bag and ball valve attachments.

4) Tygon tubing.

5) Tensiometers for monitoring the wetting front.

Procedure--The following is a listing of the procedures used with sealed double-ring infiltrometers:

1) Position the inner and outer rings on the soil liner and mark the soil surface around the edges of the ring.

2) Remove the rings and excavate trenches along the marked lines by one of the following methods:

   a) Excavate the inner ring trenches (5 cm wide x 15 cm deep) with a masonry hammer or chain saw (care should be taken not to excavate within the area under which the inner ring will be placed).

   b) Excavate the outer ring trenches (11 cm wide x 41 cm deep) with a ditch-witch.

3) Fill the trenches with a suitable grout (e.g., bentonite) and embed both rings into the trenches.

4) Fill the inner ring with water to a depth of 3 cm and test for leaks around the edges.

5) Install three tensiometers at depths of 0.15, 0.30, and 0.46 m each in the area between the rings to monitor the progress of the wetting front.

6) Slowly fill the outer ring with water in a manner that will not scour the soil and muddy the water.

7) Purge all trapped air in the inner ring by tapping on the infiltrometer with a block of wood.

8) Fill the measurement bag with water (squeeze to remove all air bubbles before closing the attached ball valve).

9) Dry and weigh the bag before connecting it to the feed tube leading to the inner ring.

10) Immediately open the valve and record beginning time for the measurement period.

11) Periodically close the valve, remove the bag, record the time, and reweigh the bag after it has been dried.

Calculations--The infiltration rate (I) and the hydraulic conductivity are calculated by Equations 22 and 23:

$$I = Q/(A\ t) \tag{22}$$

where I = infiltration rate, m/s
Q = volume of flow, m^3
A = cross-sectional area of flow, m^2
t = time interval during which flow Q occurred, s

The calculated infiltration value (I) is then used to determine hydraulic conductivity (K):

$$K = I/H \tag{23}$$

where K = hydraulic conductivity, m/s
H = hydraulic gradient = $(h + D)/D$
h = depth of water on soil, m
D = depth of wetting front, m
I = infiltration rate, m/s

Quality Assurance--As with all surface infiltration methods, it is important for the soil surface to be protected from desiccation during installation of the infiltrometer and prior to filling it with water. Three tensiometers should be installed at each soil depth and as close to the inner ring as possible (0.15 to 0.20 m).

Some form of insulation, such as 1-inch-thick styrofoam sheeting, is needed to minimize temperature changes during the test. Also, the measurement bags should be attached and removed at approximately the same temperatures so that any error due to temperature variations would be small compared with the water flux into the soil.

An SDRI is based on maintaining vertical seepage beneath the inner ring and having material beneath the liner that is free-draining. Steady-state flow is maintained and the temperature difference between water in the inner and outer ring is minimized.

Example Data--

Elsbury et al. (1988) used a combination of an underdrain, soil cores, and SDRIs that covered an area of 2.3 m^2 to determine hydraulic conductivity of a prototype soil liner in Houston, Texas (Figure 16). The underdrain showed the SDRI values to be close to that of the overall liner. Field hydraulic conductivity of the liner, as measured by the SDRIs, ranged from 3.5×10^{-7} to 2.6×10^{-6} m/s, whereas the soil cores taken from the soil liner yielded values ranging from 1×10^{-11} to 4×10^{-11} m/s.

Data from SDRIs installed in South Carolina indicated that the hydraulic conductivity of test-fill soil liners ranged from 5×10^{-9} to

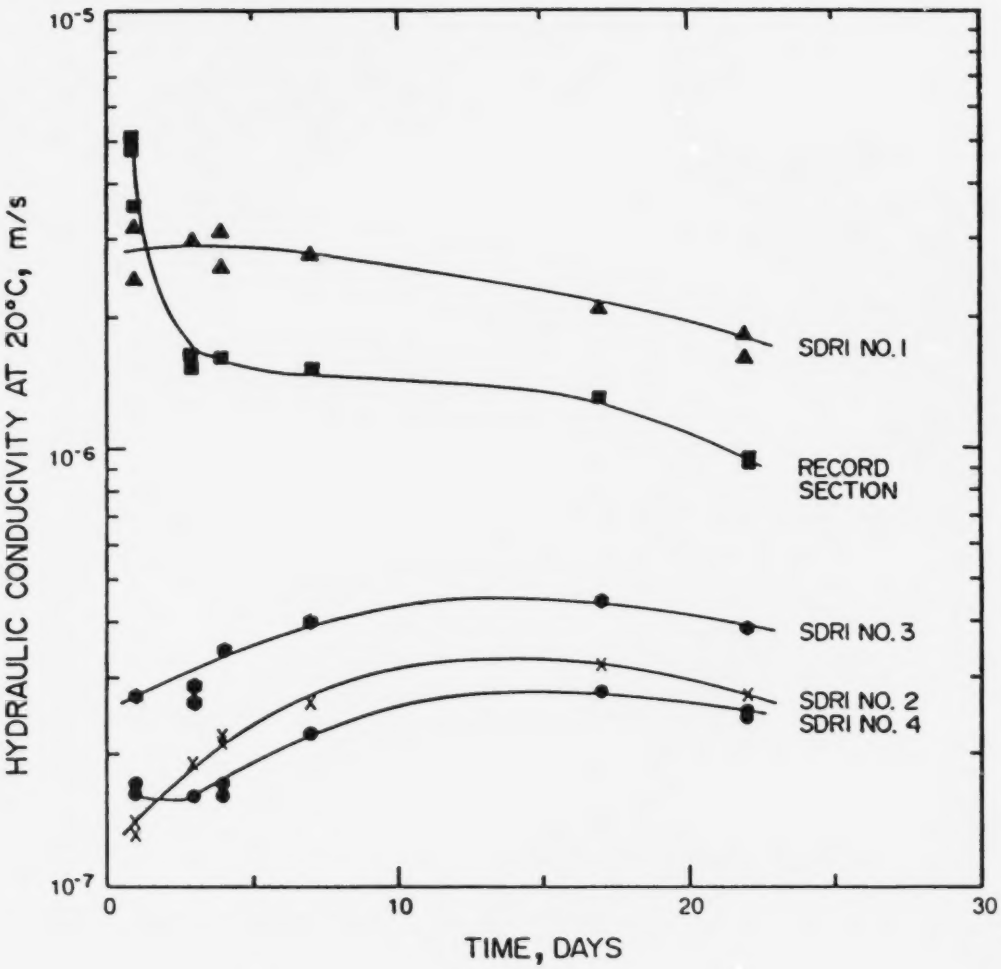


FIGURE 16. FIELD HYDRAULIC CONDUCTIVITY VALUES MEASURED WITH AN UNDERDRAIN AND FOUR SEALED DOUBLE-RING INFILTROMETERS (ELSBURY et al. 1988).

7.5×10^{-9} m/s (Anderson and Sai 1988). An SDRI used on a test-fill soil in New York found the hydraulic conductivity to be 1.1×10^{-9} m/s (Anderson and Sai 1988).

Daniel and Trautwein (1986) reported data from a site north of Niagara Falls, New York. Hydraulic conductivity (K) of two soil covers were reported to be 6×10^{-9} and 8×10^{-10} m/s.

Hsien and Yamamoto (1987) performed field and laboratory hydraulic conductivity tests on a 36 m x 24 m x 0.76 m clay liner in a test fill. The SDRI data indicated that the average hydraulic conductivity was 2.7×10^{-10} m/s, whereas a BAT permeameter gave a value of 3×10^{-10} m/s. These field results averaged one order of magnitude higher than the laboratory data.

Woodward-Clyde Consultants (1987) provided EPA with results of field infiltration tests using SDRIs on soil liners (Figure 17). The data indicated a final infiltration rate of 2.0×10^{-9} m/s at the end of 192 days.

Comments--

An SDRI is capable of measuring hydraulic conductivities of less than 1×10^{-9} m/s. The SDRI also covers a relatively large area of soil (the inner ring covers an area of 2.3 m^2). Tests conducted with SDRIs appear to confirm that the equipment can yield values representative of the overall soil liner (Elsbury et al. 1988).

In most cases, compacted soil liners are unsaturated and the infiltration rate is not in a steady state. A plot of infiltration rate versus time is needed to determine when infiltration through the soil has reached a steady state. Tests must be run for several weeks to achieve this desired steady-state condition.

Although SDRI tests require greater installation time than many methods, few ambiguities exist in this experimental method. Periodic recording of time and the measurement bag weight are the only tasks performed after the equipment is installed. The SDRI appears to yield high-quality data and presents few possibilities for yielding false low values.

COLLECTION LYSIMETERS

Collection lysimeters are placed beneath the compacted soil liner to collect liquid percolating through the liner (Elsbury et al. 1988). A perforated pipe is often installed at the low end of the lysimeter to collect and move any accumulated liquid to a solid pipe and subsequently to an access point outside the boundary of the compacted soil liner, where the liquid can be extracted and analyzed. Lysimeters have been used to monitor the quantity and quality of the leachate from landfills in Wisconsin and Canada.

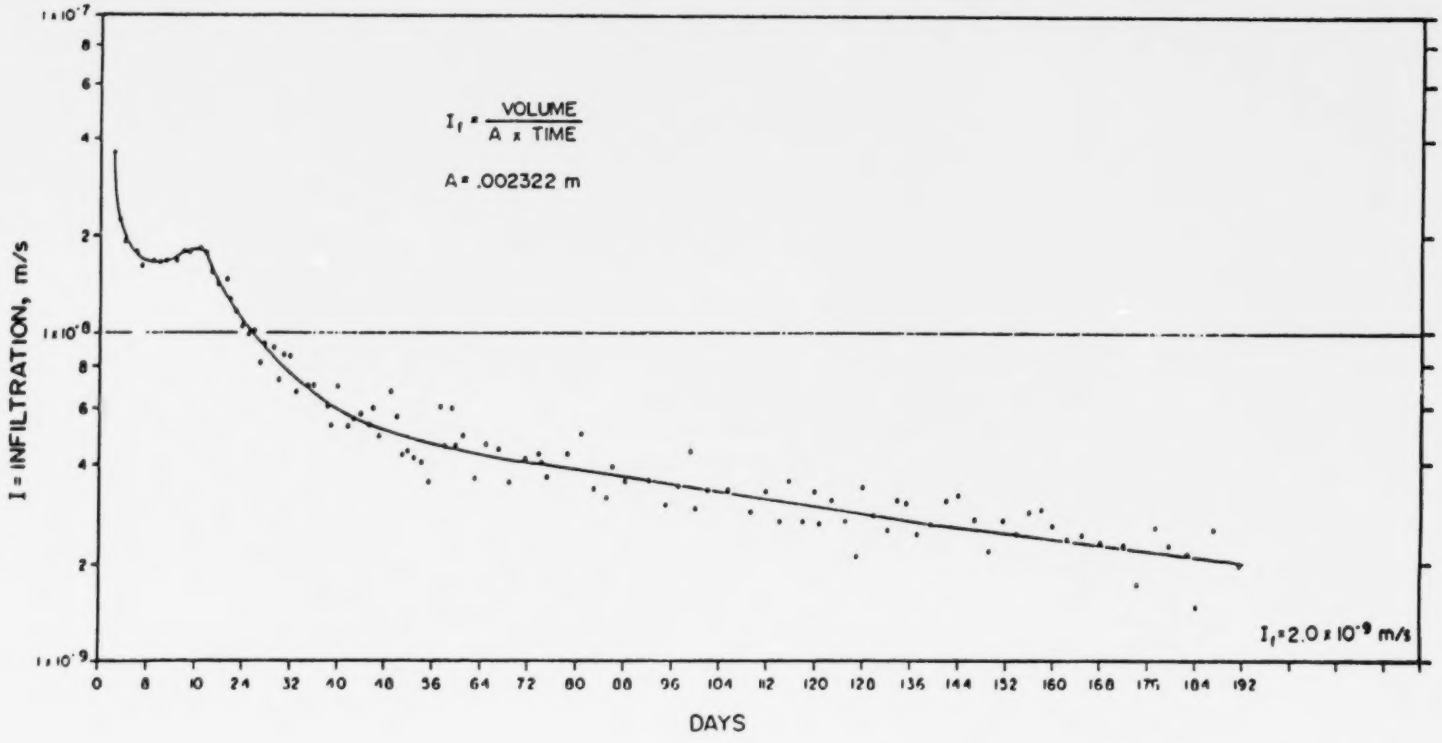


FIGURE 17. SDRI DATA FROM A SITE IN WICHITA, KANSAS (WOODWARD-CLYDE CONSULTANTS 1987).

Principles

Lysimeters operate on the principle of collecting and measuring the volume of liquid percolating through a defined area of an overlying soil liner. This method often involves installing a lysimeter around a porous drain field that is positioned directly under a compacted soil liner. The device functions by intercepting downward-moving water and diverting it into a collection system. Hydraulic conductivity is calculated by using Darcy's law and the measured flow (seepage) rate. Lysimeters should be installed at locations well above the water table to avoid the possibility of a rise in the water table affecting liquid flow into the lysimeter.

Method

Details of collection lysimeters have been discussed by Kmet and Lindorff (1983), Kmet et al. (1988), Elsbury et al. (1988), Reades (1986), Gordon et al. (1988), and Bacopoulos (1986). A summary of this information is presented in the following subsections.

Apparatus--

Figure 18 is a schematic of a collection lysimeter. Essential features of the system are as follows:

1) The collection lysimeter (a wide variety of materials have been used to construct lysimeters). The durability of the material used should be a primary selection consideration because the lysimeter cannot be replaced once it is installed. The lysimeter should be constructed with a nonreactive material (such as a geomembrane) that is less permeable than the overlying compacted soil liner. The selected material should be chemically compatible with the underlying soil and the expected liquid to be collected.

2) Clean and highly permeable granular material (less than 5% passing a 200-mesh sieve) for backfill into the lysimeter. (Material should be adequately sized to prevent puncture of the membrane used in the lysimeter.)

3) Transfer pipe(s) with substantial perforated sections inside the lysimeter.

As shown in Figure 18, the collection lysimeter has a general underdrain and an underdrain record section. Data on underdrainage were collected from the record section only. This test-fill design allowed a buffer zone of underdrainage around the zone used to calculate hydraulic conductivity. The outer general underdrain assures that only vertical underdrainage and no boundary artifacts would affect the hydraulic conductivity values measured in the underdrain record section.

Procedure--

Collection lysimeters are installed either within or below the compacted soil liner. Lysimeters installed within the soil liner give information about flow rates and leachate migration more quickly than those

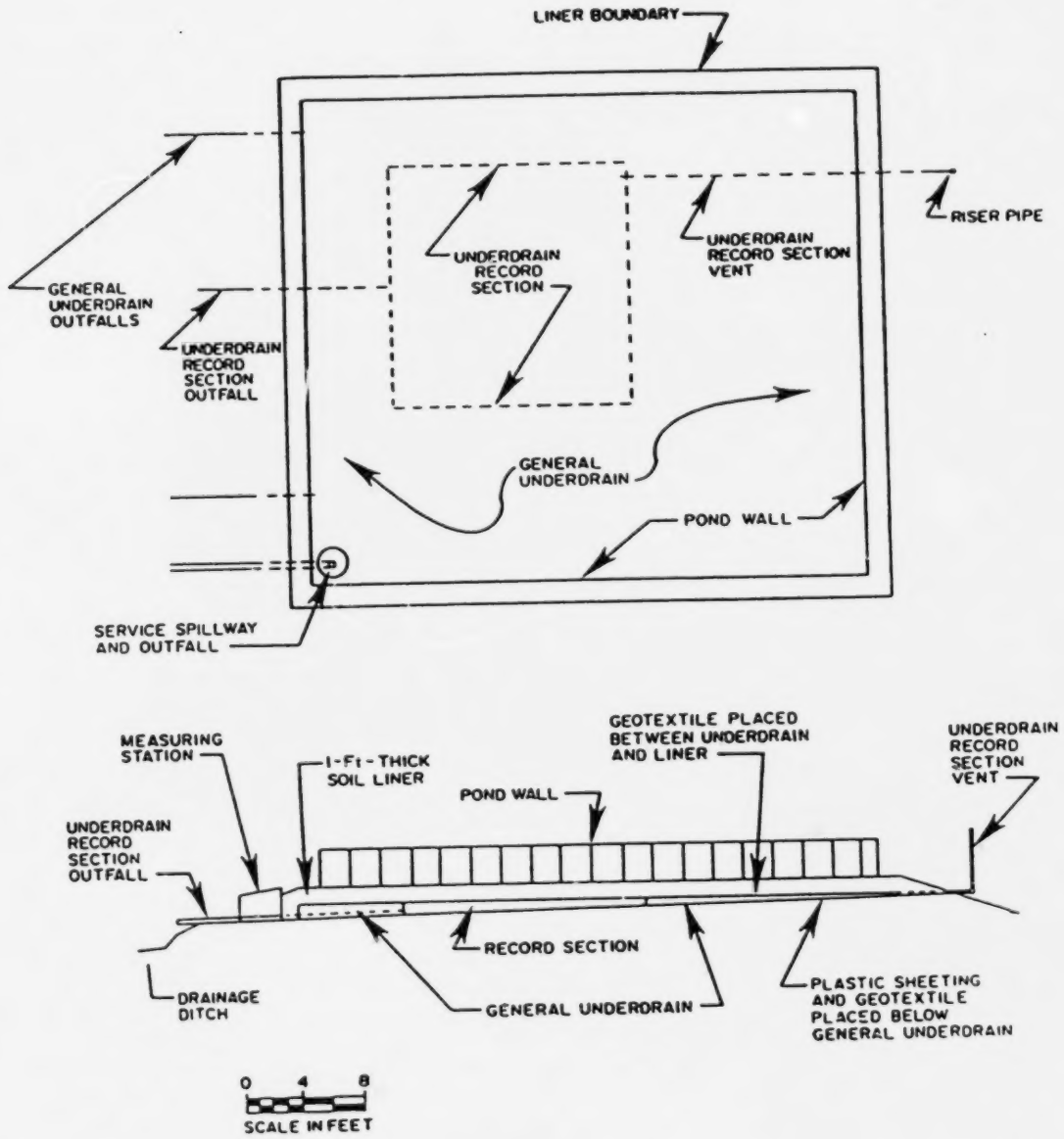


FIGURE 18. A TEST FILL EQUIPPED WITH AN UNDERDRAIN RECORD SECTION (MODIFIED FROM ELSBURY et al. 1988).

installed below the soil liner. The following is a listing of the procedures for collection lysimeters:

1) Install a flexible membrane liner (at least a 40-mm-thick sheet) of appropriate size at a predetermined depth in or below the liner; Kmet (1983) recommended a range of lysimeter sizes for use in compacted clay soils.

2) Install transfer pipes (perforated and solid) to outlet location.

3) Construct manhole and sampling riser; connect a transfer pipe to the sampling riser and the riser to the manhole.

4) Fill lysimeter with sand and wet to field capacity before compacting soil liner on top to the specified thickness.

5) Periodically collect and measure accumulated liquid. (With low-hydraulic-conductivity soil liners it may be years before liquid accumulates in the lysimeter.)

6) Calculate hydraulic conductivity.

Calculations--

Equation 24 is used to calculate the hydraulic conductivity of the compacted soil liner above the collection lysimeter.

$$K = Q/HA \qquad (24)$$

where K = hydraulic conductivity, m/s
Q = volume of liquid collected per unit time, m^3/s
H = hydraulic gradient = $(h + L)/h$
A = cross-section area of lysimeter, m^2
h = liquid head on soil liner, m
L = compacted soil liner thickness, m

Quality Assurance--

As with every other method discussed in this document, the accuracy of determining the quantity of liquid collected by the collection lysimeter determines the quality of the data produced. The greater the quantity of liquid collected, the lower will be the error involved in measuring the volume of liquid that percolated through the soil liner. The lysimeter used should be large enough to insure that the system intercepts a representative number of macropores.

Collection lysimeters used in compacted soil liner tests require substantial time for steady flow conditions to develop (weeks or months). Tests should be run and data plotted to show that steady-state conditions have been achieved.

Example Data

Bacopoulos (1986) monitored flow rates from three 225-m^2 lysimeters within and below a compacted clay liner to determine the hydraulic conductivity of the compacted clay liner at the Keele Valley Landfill site in Toronto, Canada. Flow rates from the lysimeters, which were installed within the liner in 1984, indicated that the hydraulic conductivity at the end of June 1985 was less than 1×10^{-10} m/s. No flow was observed in the lysimeters installed below the clay liner at the end of the measurement period.

Reades (1986) presented detailed monitoring data from the Keele Valley Landfill. Laboratory hydraulic conductivity data were compared with data from the 225-m^2-area lysimeter. The hydraulic conductivity data from the lysimeter installed within the clay liner were found to range from 8.0×10^{-11} to 9.8×10^{-11} m/s, with a mean of 8.8×10^{-11} m/s. The laboratory hydraulic conductivities of samples from the site during the three construction seasons had geometric means ranging from 7.7×10^{-11} to 8.2×10^{-11} m/s.

Elsbury et al. (1988) presented data on a collection lysimeter from a site in Houston, Texas, and compared the data from four sealed double-ring infiltrometers with laboratory data. The hydraulic conductivity of the compacted soil liner determined with the lysimeter was 1.8×10^{-6} m/s, whereas the SDRI showed the conductivity to range from 3.5×10^{-7} to 2.6×10^{-6} m/s (Figure 16).

Gordon et al. (1988) presented information on collection lysimeters at three active, full-scale, clay-lined landfills in Wisconsin. Five to seven years of data on the quantity of liquid collected from these lysimeters were used to estimate field hydraulic conductivity by using Darcy's law and the measured or estimated leachate head. Table 7 presents the data from two of the landfills. These data indicate that the hydraulic conductivity of the compacted soil liner at the two sites was lower than 1×10^{-9} m/s.

The average laboratory hydraulic conductivity values for compacted clay samples from Portage County Landfill ranged from 1×10^{-11} to 3×10^{-11} m/s, whereas the values for Sauk County Landfill ranged from 8×10^{-11} to 4×10^{-10} m/s.

Comments

Collection lysimeters can measure hydraulic conductivities of less than 1×10^{-9} m/s. If the lysimeters are large enough, they are also capable of yielding hydraulic conductivity values that are representative of the overall soil liner. The collection lysimeters used by Elsbury et al. (1988) were approximately 19.4 m^2, which proved to be large enough to yield representative values. The main drawback of this method is that it can take months to obtain steady-state hydraulic conductivity values. Unlike infiltrometers, which give initially high values that decrease to a low steady-state value, collection lysimeter values typically begin very low and gradually build up to a higher steady-state value. Consequently,

the testing period may well interfere with construction of a facility, and the adequacy of a particular soil liner design may not be known until the end of a long test period.

TABLE 7. RANGE OF HYDRAULIC CONDUCTIVITY VALUES FOR VARYING LEACHATE HEADS AT TWO CLAY-LINED LANDFILLS IN WISCONSIN

Location	Leachate head, m	Gradient	Hydraulic conductivity, m/s
Portage County Landfill	0.03	1.0	9.1×10^{-11}
	0.15	1.1	8.3×10^{-11}
	0.30	1.2	7.6×10^{-11}
	0.61	1.4	6.5×10^{-11}
	0.91	1.6	5.7×10^{-11}
	1.22	1.8	5.1×10^{-11}
	1.52	2.0	4.6×10^{-11}
	3.05	3.0	3.0×10^{-11}
	6.10	5.0	1.8×10^{-11}
	9.15	7.0	1.3×10^{-11}
Sauk County Landfill	0.03	1.0	4.0×10^{-10}
	0.15	1.1	3.6×10^{-10}
	0.30	1.2	3.3×10^{-10}
	0.61	1.4	2.8×10^{-10}
	0.91	1.6	2.5×10^{-10}
	1.22	1.8	2.2×10^{-10}
	1.52	2.0	2.0×10^{-10}
	3.05	3.0	1.3×10^{-10}
	6.10	5.0	7.9×10^{-11}
	9.15	7.0	5.7×10^{-11}

Tests comparing collection lysimeters and large infiltrometers have shown that the values obtained by each method are relatively close. Consequently, if a collection lysimeter is desired, concurrent testing of the soil liner should be conducted with large infiltrometers. This procedure could save months of waiting for results definitive enough to begin construction of a facility.

Construction of a collection lysimeter is time-consuming and requires skilled personnel. Special care must be exercised to ensure that the flexible membrane underlying the collection field is not damaged during construction. Because such damage could result in false low hydraulic conductivity values, concurrent testing of the soil liner with large infiltrometers is recommended. Ultimately, a large collection lysimeter has the potential for yielding the most accurate values for quantification of the volume and rate of liquid that moves through a compacted soil liner. In practice, however, the response time of a lysimeter limits its utility for short-term tests.

METHODS UNDER CURRENT STUDY

Velocity permeameters and porous plate infiltrometers are both under current study for their applicability to measuring the hydraulic conductivity of compacted soils. Sufficient data are not currently available to determine the adequacy of either method in this application; however, both methods show promise and are briefly discussed here.

Velocity Permeameter

A velocity permeameter is used to measure the in situ hydraulic conductivity of a soil. This method is based on monitoring the time it takes a water column to fall through a distance, Δh. The rate of fall of the water column depends on the rate of water entry into a soil core enclosed within the coring tube. A Hewlett Packard 41CX calculator equipped with a timing module is used to determine the rate of fall of the water column. The rate is then used as input to a program in the calculator that computes the hydraulic conductivity.

Principles--

A velocity permeameter uses a small computer to determine in situ hydraulic conductivity from falling-head infiltration data. The method involves the use of a calculator equipped with a timing module to enter data on change of water level in a water column with time. These data are used in a computer program to convert the information into hydraulic conductivity values. This method involves determination of a series of hydraulic conductivity values on the same in situ soil core and plotting these values with time.

Method--

Apparatus--Figure 19 is a schematic diagram of the velocity permeameter. The main components of this permeameter are as follows:

1) Soil coring device.

2) Head tube with scale.

3) Outer tube with driver and coupler.

4) Opening for filling with water.

5) Hewlett Packard 41CX calculator equipped with a timing module and an expanded memory module.

6) Printer.

Procedure--The following is a listing of the procedures for installing and using a velocity permeameter:

1) Select test area.

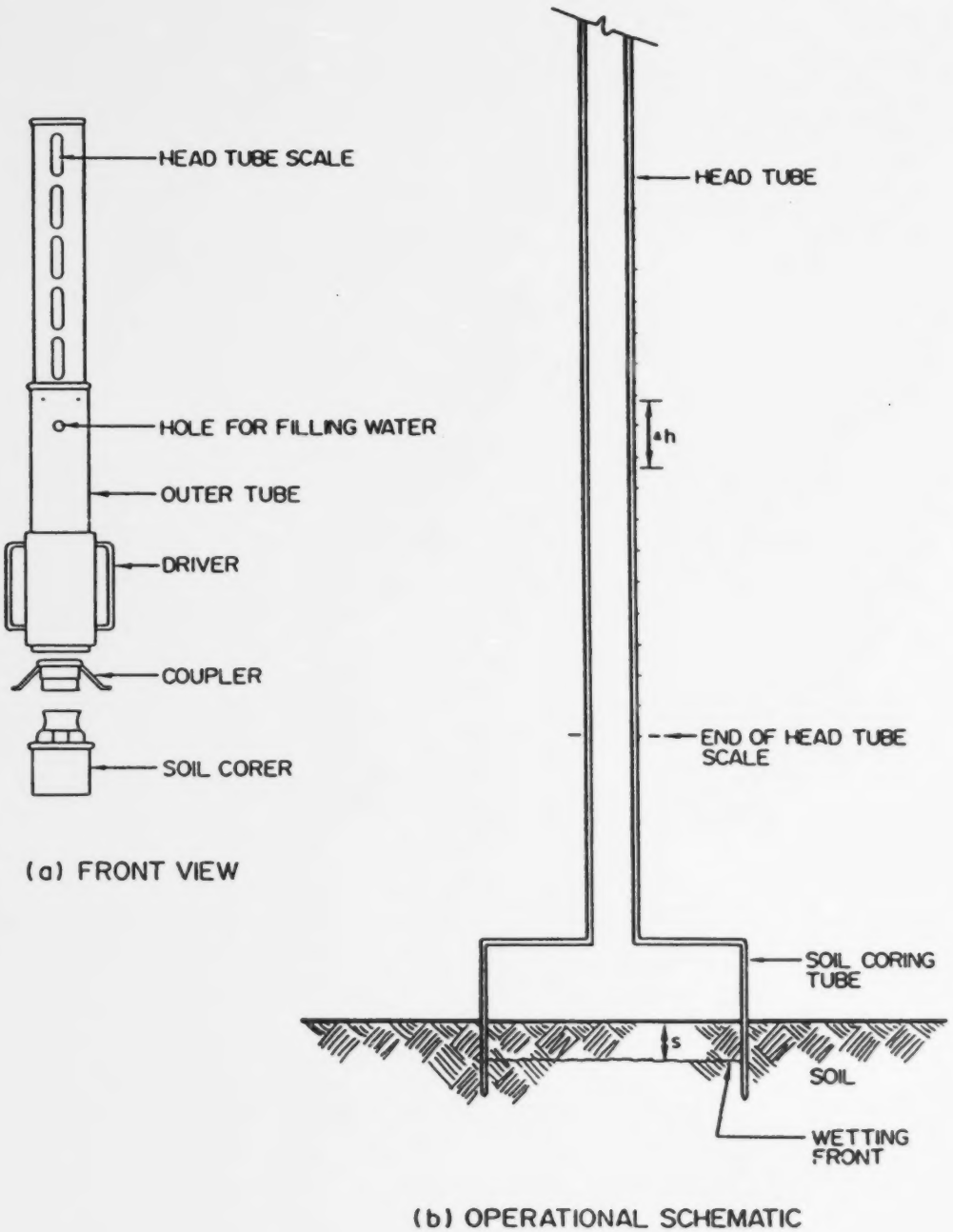


FIGURE 19. SCHEMATIC OF A VELOCITY PERMEAMETER. (MODIFIED FROM KANWAR et al. 1987).

2) Position coring device (corer) on soil and drive it into the soil with the driver.

3) Attach outer and head tubes to corer by using the attached coupler (Figure 19).

4) Fill the tubes with water through the tube opening.

5) Record the time and water level in head tube.

6) Record and store the time it takes the water level in the head tube to fall through a fixed increment of distance (dh) measured off the head tube scale.

7) Calculate the rate of change of flow with respect to head (dv/dh).

8) Determine the hydraulic conductivity of the soil in corer by using the computer program and the Hewlett Packard (HP) 41CX calculator.

Calculations--The following equation is used in the H-P calculator to determine the hydraulic conductivity by the velocity permeameter method:

$$K_s = S\ (dv/dh) \tag{25}$$

where K_s = hydraulic conductivity measured in direction of flow, m/s
S = depth of wetting front, m
dv = rate of water drop in head tube, m/s
dh = change in head of water in the head tube, m

Equation 26 can be used in the absence of the H-P calculator to determine the apparent hydraulic conductivity of a soil.

$$K_a = C\ dv/dh \tag{26}$$

where K_a = apparent hydraulic conductivity, m/s
$C = (A_t\ S)/A_c$
A_t = cross-sectional area of head tube, m^2
A_c = cross-sectional area of soil core, m^2
S = depth of wetting front, m
dv = rate of water drop in head tube, m/s
dh = change in head of water in head tube, m

During field tests, a series of K_a are determined and plotted over time (Figure 20). This plot shows a decrease in hydraulic conductivity followed by a slight increase after some low value has been attained. Merva (1987) states that the apparent hydraulic conductivity is the least value noted before the slight increase in the conductivity value occurs. This low value occurs when the soil sample is completely wet and just before the wetting front moves into the soil beneath the core.

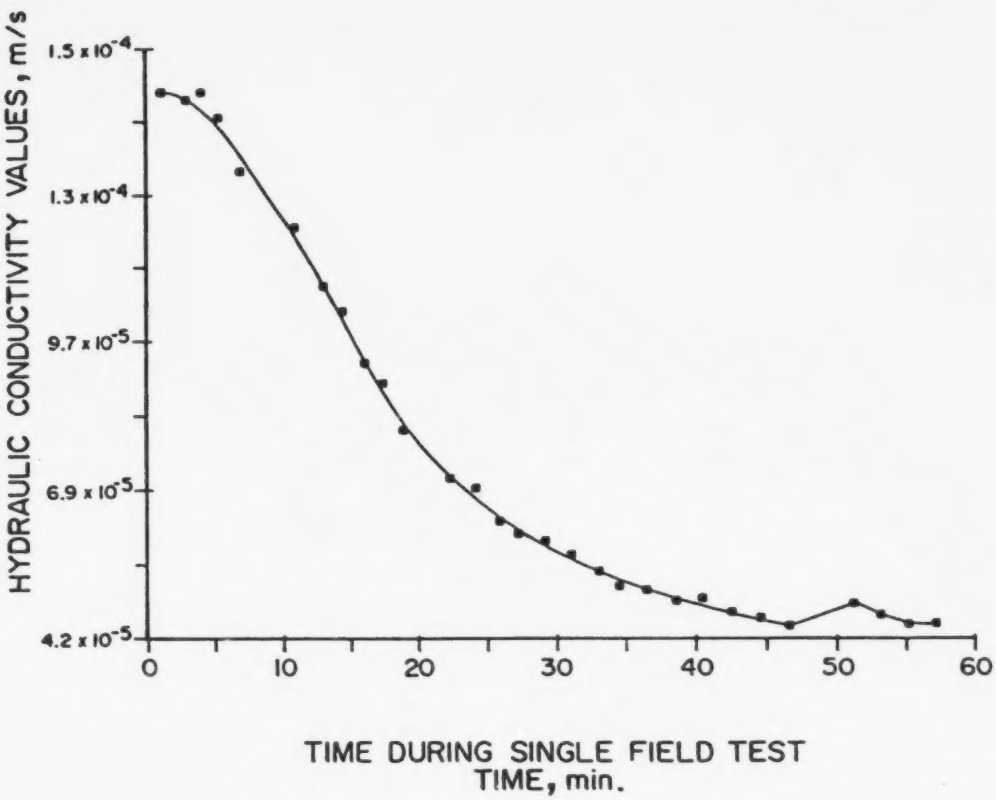


FIGURE 20. APPARENT HYDRAULIC CONDUCTIVITY VERSUS TIME AS MEASURED WITH THE VELOCITY PERMEAMETER (MODIFIED FROM MERVA 1987).

Quality Assurance--The method depends on accurate determination of the velocity of the fall of water in the head tube, and this depends greatly on the person recording the value and on the ratio of the soil cross-sectional area to the area in the head tube. The larger the soil core and the smaller the diameter of the head tube, the more accurate the values collected will be.

Example Data--

Rogers et al. (1987) used the velocity permeameter to determine vertical and horizontal hydraulic conductivities of Commerce silt loam soil at a site in Baton Rouge, Louisiana. The range and mean values determined in this study were compared with data from 36 auger-hole tests from the same area. The auger-hole tests indicated the soil had a mean hydraulic conductivity value of 5.1×10^{-6} m/s at an average hole depth of 56 cm. Hydraulic conductivity values measured with the velocity permeameter ranged from 5.6×10^{-7} to 2.0×10^{-6} m/s.

Comments--

Velocity permeameters measure the hydraulic conductivity of small areas, and the values obtained may not be representative of the overall soil liner. This method has not been tested on compacted soil liners, and further tests are needed to determine whether it is capable of measuring hydraulic conductivities of 1×10^{-9} m/s and less. Difficulties have been reported in sealing the edges of the coring device under high liquid heads. Also, the data acquisition and reduction technique involved in this method may demand the time of a skilled operator.

Porous Plate Infiltrometers

Porous plate infiltrometers use water infiltration under tension to estimate hydraulic conductivity. A porous plate is placed on the soil surface to supply water to the soil, and the flow rate from a supply reservoir is used to calculate the infiltration of water into the soil. Variations of this infiltrometer have been used by several researchers [i.e., Dirksen (1975), Clothier and White (1981), Moore et al. (1986), Ankeny et al. (1988), and Baumgartner et al. (1987)]. The following subsections describe only two of these designs because the basic principles and methods are similar in all the variations. The automated tension infiltrometer (Ankeny et al. 1988) and the Guelph infiltrometer (Baumgartner et al. 1987) are the designs addressed.

Principles--

The automated tension infiltrometer (ATI) automatically measures the height of water in a Mariotte column for use in calculating the volume of water infiltrating into the soil. Water flows from the Mariotte column to a porous plate placed on the soil surface, which distributes the water to the soil profile. Changes in water level in the Mariotte column are measured automatically by using the difference in tension between two pressure transducers, one at the top and one at the bottom of the Mariotte column. This method requires two tests to solve a system of simultaneous equations needed to calculate the hydraulic conductivity of the soil. Each test is run with a different size porous plate.

The Guelph infiltrometer (GI) is a modified Guelph permeameter (GP) with an attached disk that allows it to be used for measurements at the surface with little disturbance of the soil surface. The analysis is similar to that used for the GP except that the GI uses a zero depth of water in the borehole (H = 0). In addition, the GI is set up on the soil surface rather than in a borehole as with the GP. The field saturated hydraulic conductivity is obtained by using two or more measurements of the wetted surface of the disk attachment.

Method--

The ATI involves determination of two series of data for infiltration rate versus time. The test is run with a particular size porous plate until a steady-state condition is achieved. This procedure is repeated with a different size plate until a steady state is attained. The GI method is similar to the GP method except in those areas discussed in these subsections.

Apparatus--Figure 21 is a schematic diagram of the ATI. The main features are listed here:

1) Soil contact base (porous plate/faceplate) 0.10 and 0.15 m diameter with a 2-mm hole per 10-mm^2 area.

2) Bottom and top transducers.

3) Bubbling tube.

4) Bubble tower.

5) Air entry ports with valves.

6) Mariotte column.

7) Septum.

8) Data logger.

9) 400-mesh nylon filter.

The schematic of the GI (Figure 22) shows the design of the disk attachment and a second Mariotte attachment (cartridge). Essential features are listed here:

1) Nylon mesh disk.

2) Support screen.

3) Air tip seating washer.

4) Existing main body of Guelph permeameter.

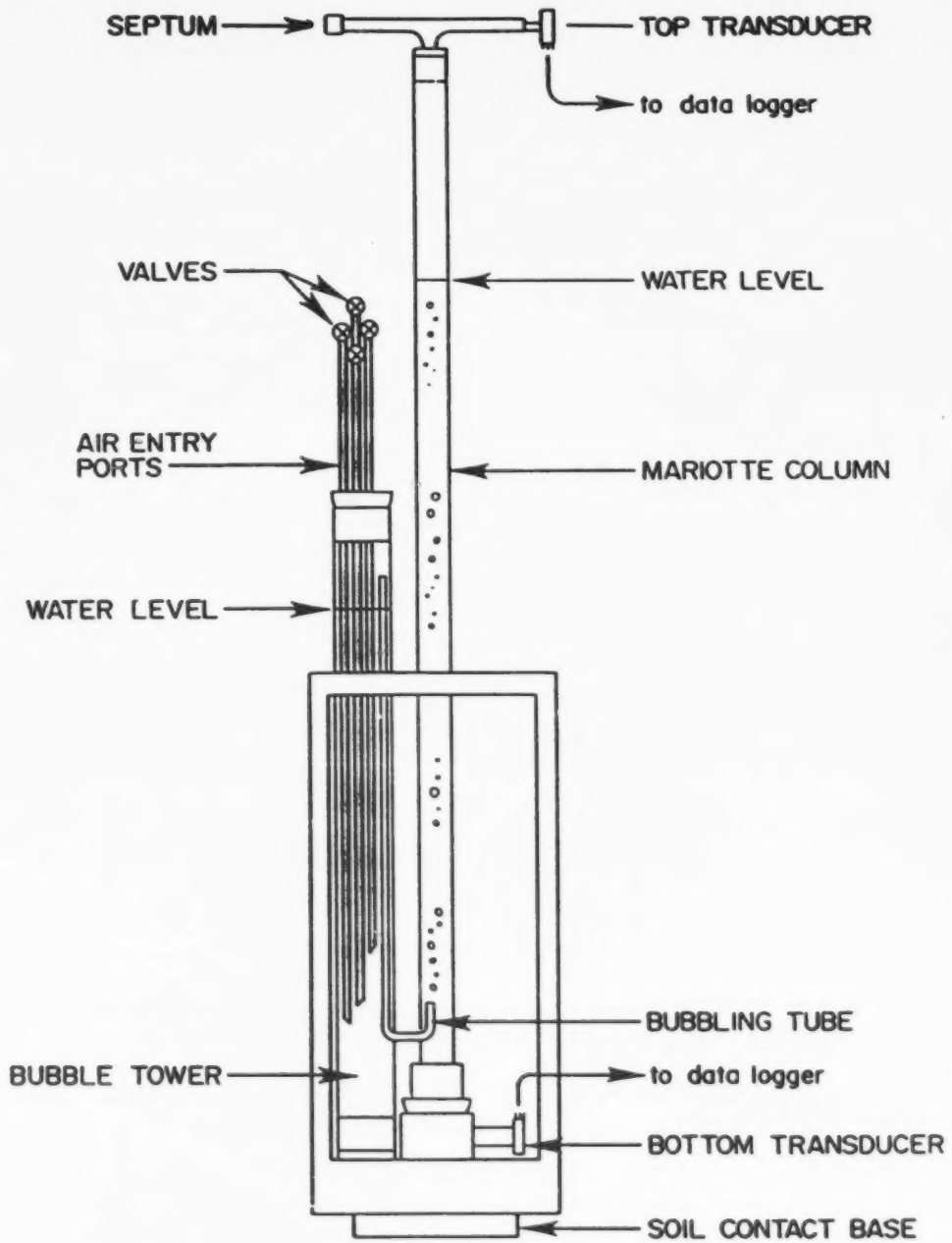


FIGURE 21. SCHEMATIC OF AN AUTOMATED TENSION INFILTROMETER (ANKENY et al. 1988).

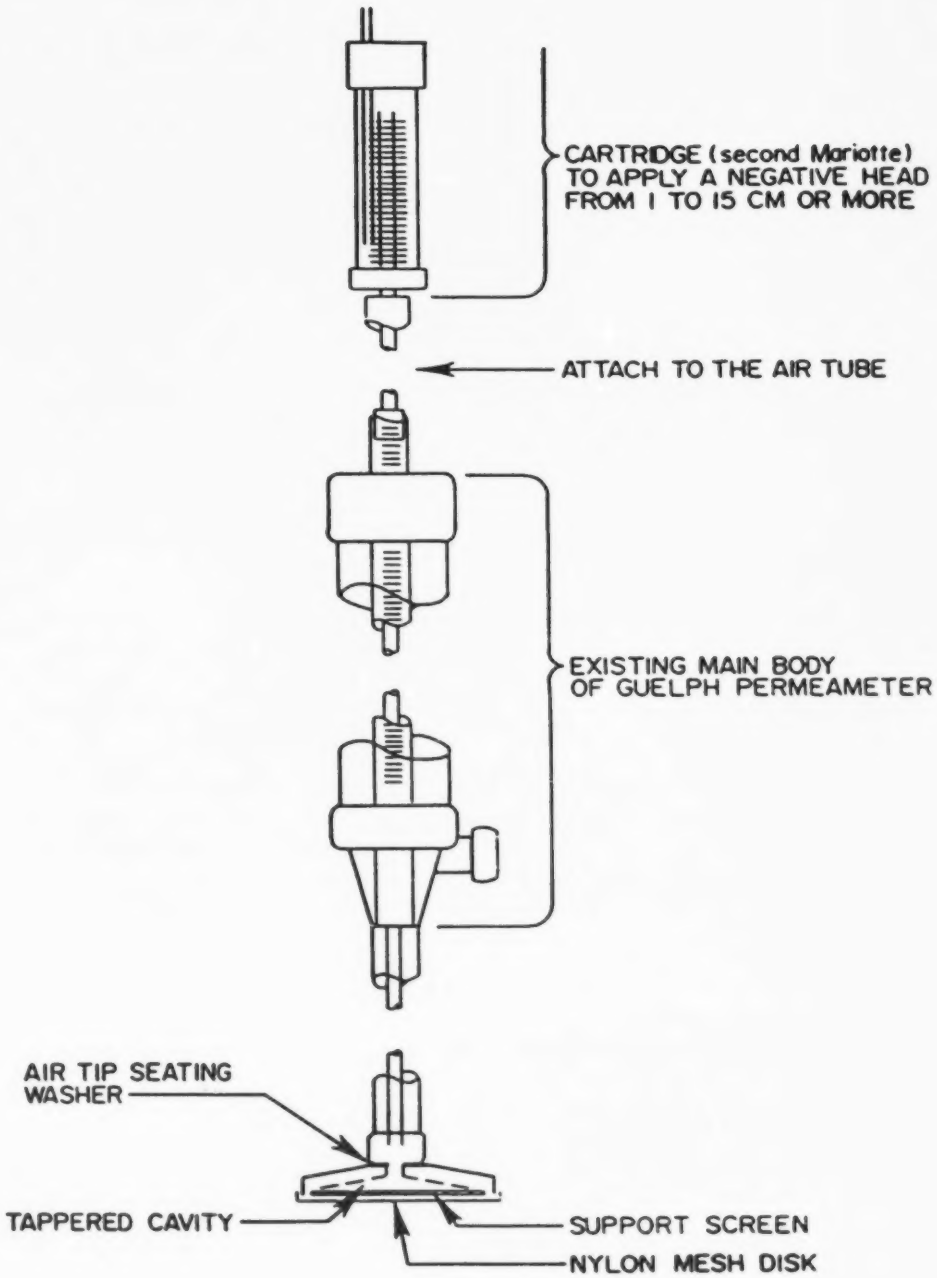


FIGURE 22. SCHEMATIC OF GUELPH INFILTROMETER (BAUMGARTNER et al. 1987).

5) Cartridge (second Mariotte supply tube).

Procedure--The following is a listing of the procedures used for installation and operation of the ATI:

1) Assemble the infiltrometer with a known size porous plate.

2) Record Mariotte column diameter.

3) Place a 400-mesh nylon filter (air-entry value of about 250 mm of water) on the soil.

4) Place assembled infiltrometer on the filter (align contact base with filter).

5) Fill Mariotte column with water.

6) Open one of the valves on the air-entry ports to allow water to flow to the porous plate at a predetermined tension (ports can be set to tensions of 0.02 to 0.5 m by operation of the appropriate valve).

7) Program data logger to record paired readings of top and bottom transducers at regular intervals.

8) Repeat Steps 1 through 7 with a different size porous plate.

Procedures for the GI are as follows:

1) Measure the radius of the disk(s).

2) Assemble the infiltrometer.

3) Fill the reservoir and cartridge with water.

4) Place infiltrometer on soil surface. (A thin layer of sand is required on the surface to ensure good contact between the porous plate and the field soil.)

5) Start infiltrometer by raising the air-inlet tube out of the outlet port.

6) Monitor the rate of fall of water level in the cartridge/reservoir until a steady rate is attained.

7) Record the radius of the disk (wetted surface of disk attachment).

8) Change the disk attachment and repeat Steps 2 through 7.

9) Calculate the field saturated hydraulic conductivity by the simultaneous equation approach by using Equation 31 or the least squares analysis.

Calculations--Equation 27 is used with the ATI to calculate the saturated hydraulic conductivity of the soil:

$$K_{sat} = (I_1 r_1 - I_2 r_2)/(r_1 - r_2) \quad (27)$$

where K_{sat} = saturated hydraulic conductivity, m/s
r_1 and r_2 are radii of the infiltrometer soil contact base, m
I_1 and I_2 are the steady infiltration rates using soil contact bases r_1 and r_2 respectively, m/s

Wooding (1968) presented calculations for use with the GI. For a surface disk with zero ponding, he showed that the steady-state three-dimensional intake rate is given by:

$$Q = r^2 K_{fs} + 4 \; ro_m \quad (28)$$

where Q = steady-state water flow rate, m^3/s
r = radius of the wetted surface of disk, m
K_{fs} = field saturated hydraulic conductivity, m/s
o_m = matric flux potential, m^2/s

For the two-ring method shown in the procedures, K_{fs} is obtained by use of the simultaneous equation approach:

$$K_{fs} = M_2 Q_2 - M_1 Q_1 \quad (29)$$

where $M_1 = r_2/(r_1 r_2 [r_2 - r_1])$ $(1/m^2)$
$M_2 = r_1/(r_1 r_2 [r_2 - r_1])$ $(1/m^2)$
r_1 = radius of wetted surface of Disk 1, m
r_2 = radius of wetted surface of Disk 2, m
Q_1 = steady-state flow rate using Disk 1, m^3/s
Q_2 = steady-state flow rate using Disk 2, m^3/s

Quality Assurance--A primary problem with the porous plate method is obtaining sufficient sensitivity in the instruments to measure low hydraulic conductivity rates. Larger-diameter porous plates and small-diameter reservoir tubes may be used to improve the sensitivity of these instruments.

Example Data--

No data are available on the use of an ATI with compacted clay soils. Data provided by Ankeny et al. (1988) for a coarse sand showed that the method can be used to measure hydraulic conductivities of 1×10^{-8} to 5×10^{-4} m/s. The studies were done on a 0.01- to 0.02-m^2 area of soil. Research is continuing on the use of the tension infiltrometer to determine field hydraulic conductivity of clay liners over a larger area.

No field data are yet available on the use of the GI on compacted soil liners. A series of tests on compacted soil liners were planned for the spring of 1989 at the University of Guelph.

Comments--

The porous plate methods which essentially evaluate unsaturated hydraulic conductivity, are currently being adapted for use on saturated soils. No data are available on soils with hydraulic conductivities of 1 x 10^{-9} m/s or less. Only small areas of soil have been evaluated with this method; therefore, results may not be representative of the overall soil liner. Further testing of this method on compacted clay soils is planned by U.S., Canadian, and Australian researchers. Investigation of the effect of bigger disk diameters on the determination is also planned. The method has promise for distinguishing between the overall field hydraulic conductivity and the component of flow resulting from macropores. At the time of issuance of this report, however, research had not progressed far enough to suggest the engineering community's use of this method on soil liners.

SOIL CORES EVALUATED IN THE LABORATORY

A variety of methods are available for obtaining the hydraulic conductivity of soil cores in the laboratory. Several of these methods have been discussed by U.S. EPA (1984) and Goldman et al. (1988). Laboratory methods are not believed to provide a reliable indicator of field performance of clay liners (U.S. EPA 1985). Because widespread use has been made of laboratory hydraulic conductivity tests as indicators of field performance, some of these methods are briefly discussed here.

Principles

A compacted soil liner can be evaluated by collecting relatively undisturbed cores for use in hydraulic conductivity tests in a laboratory setting. Soil liner samples can either be carved out of the soil or collected by pushing a thin-walled tube into the soil. The samples collected in the thin-walled tubes can either be tested while in the tube (fixed-wall permeameter) or removed from the tube, trimmed, and placed in a flexible-wall permeameter.

Methods

The following discussion covers fixed-wall and flexible-wall permeameters and the constant-head method used to calculate hydraulic conductivity. The falling-head method for calculating hydraulic conductivity is not discussed in this document because it has limited utility with tests on low-hydraulic-conductivity compacted soils. In general, high pressures are applied in tests on compacted materials to speed testing time. The pressures used are typically equivalent to a height of water of several meters. Consequently, any liquid level drop in the water supply burette used in a falling-head method would be negligible compared to the total applied pressure.

Apparatus--

Fixed-Wall Permeameter--The following is a list of the parts of a fixed-wall permeameter (Figure 23):

1) Double-ring base plate (optional).

2) Gaskets.

3) Top plate with pressure input port.

4) Inner ring leachate outlet.

5) Outer ring leachate outlet.

Flexible-Wall Permeameter--The following is a list of the parts of the flexible-wall permeameter (Figure 24):

1) Steel pedestal under a porous plate.

2) Soil sample encased in a flexible membrane.

3) Steel cap over a porous plate.

4) Liquid feed lines.

5) Liquid supply reservoir.

Procedures--

Fixed-Wall Permeameter--The following is a listing of the procedures required in the use of a fixed-wall permeameter:

1) Press stainless steel cylinder into soil liner.

2) Retrieve cylinder with soil; cap both ends of cylinder for transportation to laboratory.

3) Remove end cap from bottom of cylinder.

4) Gently scrape away soil to level the surface of the sample to approximately 1.3 cm from the bottom of the cylinder.

5) Place geotextile fabric into the double-ring insert and press the insert on the soil.

6) Place base plate with four allthreads over the insert. (An O-ring gasket should be placed between the base plate and the base of the cylinder.)

7) Turn sample over and place a filter or geotextile fabric on the soil surface.

8) Place an O-ring in the groove on the inside of the plate.

9) Place the top plate over the threads and down onto the cylinder, making sure the cylinder fits into the groove with the O-ring.

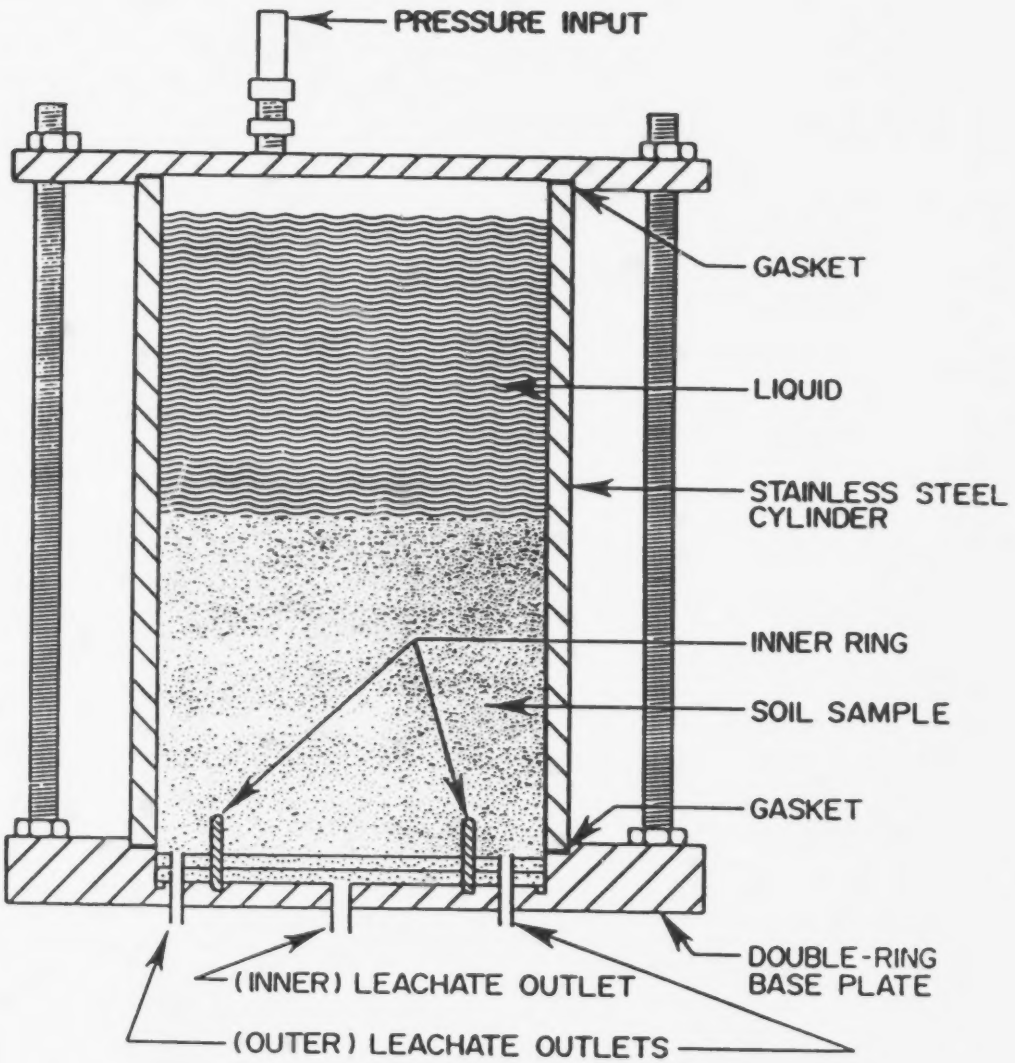


FIGURE 23. SCHEMATIC OF A FIXED-WALL PERMEAMETER (MODIFIED FROM DANIEL et al 1985.)

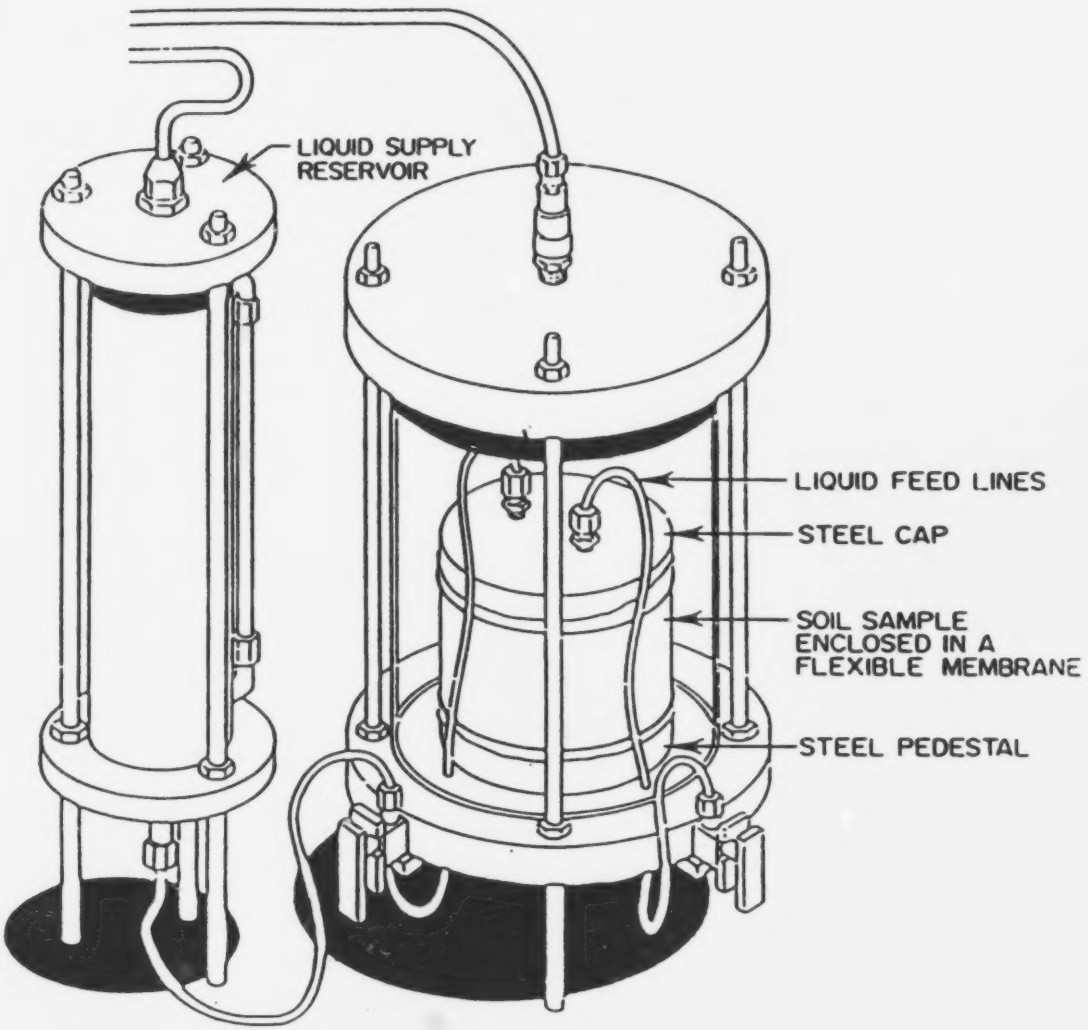


FIGURE 24. FLEXIBLE - WALL PERMEAMETER.

10) Tighten down the top plate with hex nuts.

11) Apply liquid to the top of the soil.

12) Fit pressure source to assembled permeameter and place liquid collection flasks on the inner and outer leachate outlets.

13) Apply low pressure to the liquid and record time and pressure.

14) Periodically record the time, volume of liquid in the flasks, and the pressure on the liquid.

15) Pass liquid through the soil until steady-state flows have been attained in both the inner and outer compartments.

Flexible-Wall Permeameter--Flexible-wall hydraulic conductivity tests are performed in triaxial permeameters. The following procedures apply to he permeameter shown in Figure 24:

1) Extrude the soil sample from a Shelby tube.

2) Trim sample to desired size.

3) Place porous plate on the steel pedestal.

4) Place trimmed sample on top of the porous plate.

5) Place a porous plate on top of the soil and put the steel cap on top of the plate.

6) Place a flexible membrane over the steel cap, soil sample, and steel pedestal.

7) Secure flexible membrane to the steel pedestal and steel cap with suitable rubber bands.

8) Place prepared soil sample on base plate.

9) Connect pressure lines and reservoirs.

10) Apply appropriate confining pressure and back pressure to saturate soil fully.

11) Apply liquid under required pressure to the top of the soil to start test.

Calculations--

Hydraulic conductivity tests done in the laboratory on compacted soil samples are typically conducted by the constant-head method. Calculations used in these determinations are provided here. The constant-head method involves applying water to the soil with a constant pressure and measuring the quantity of water that is discharged in a given period of time. The

head loss across the soil thus remains constant throughout the test, and a form of Darcy's Equation (Equation 30) is used to calculate the hydraulic conductivity of the soil.

$$k = Q/(A\ i\ t) \qquad (30)$$

where k = hydraulic conductivity, m/s
Q = quantity of flow in a given time, m^3
i = hydraulic gradient = H/L
H = hydraulic head difference, m
L = depth of soil, m
A = area of flow, m^2
t = time for flow measurement, s

The two main techniques used to maintain constant head are 1) the use of a large reservoir of water so that the volume of water lost from the reservoir during the test will cause a negligible change in reservoir water level, and 2) the use of a Mariotte bottle arrangement.

Quality Assurance--

Laboratory samples are usually too small to include a representative distribution of the macrofeatures present in a soil liner. Because soil imperfections may be widely spaced, it may not be practical to collect samples in the field that are large enough to assure that the laboratory test yields representative hydraulic conductivity values.

Example Data

A prototype compacted soil liner was constructed, and determinations of hydraulic conductivity were made by laboratory and field methods. (Elsbury et al. 1988). Laboratory hydraulic conductivity values obtained on Shelby tube samples in flexible-wall permeameters ranged from 1×10^{-9} to 1.0×10^{-11} m/s. Hydraulic conductivity values obtained with samples compacted in the laboratory in fixed-wall permeameters ranged from 2×10^{-10} to 1×10^{-11} m/s. Field hydraulic conductivity values obtained with a sealed double-ring infiltrometer ranged from 2.6×10^{-6} to 2.0×10^{-7} m/s.

Nordquist et al. (1986) measured hydraulic conductivity of Shelby tube samples taken from three test-fill liners in Oklahoma and Utah. The average hydraulic conductivity value obtained from these samples in fixed-wall permeameters was 3×10^{-10} m/s, whereas the average field hydraulic conductivity value obtained with the air-entry permeameter was 3×10^{-10} m/s. These data showed that the laboratory and field data were within one order of magnitude (Table 2).

Day and Daniel (1985) presented summary and comparison data on laboratory and field hydraulic conductivity of a compacted clay liner (Table 8). Hydraulic conductivity values determined in the laboratory were two to three orders of magnitude lower than the field-determined values.

TABLE 8. COMPARISON OF FIELD AND LABORATORY HYDRAULIC CONDUCTIVITY DATA.

Type of hydraulic conductivity test	Average hydraulic conductivity, m/s	
	Clay 1	Clay 2
Pond test on entire liner	9×10^{-8}	4×10^{-8}
Laboratory test (all types) on laboratory compacted samples	1×10^{-10}	2×10^{-11}
Laboratory tests (flexible-wall) on hand-carved samples	1×10^{-10}	3×10^{-11}
Laboratory tests (flexible-wall) on Shelby tube samples	1×10^{-10}	3×10^{-11}
Laboratory tests on hand-carved samples trimmed into consolidation ring and tested at an effective stress of 96 kPa	1×10^{-9}	4×10^{-10}
Ring infiltration test in field	5×10^{-8}	3×10^{-8}

Comments

Laboratory hydraulic conductivity tests can measure very low hydraulic conductivity values; however, using these values to represent field conditions presents several problems. Laboratory samples used to determine hydraulic conductivities are typically too small to have a representative distribution of the macropores present in the field. Consequently, these tests tend to give values that are one to three orders of magnitude lower than the actual field values. Application of confining pressure on the sample during flexible-wall tests also may seal or reduce the size of any macropores present in the soil sample. The absence and/or reduction of the macropores will result in a lower hydraulic conductivity than that of the actual liner.

Side-wall leakage can be significant in laboratory tests, and every effort should be made to minimize this effect in laboratory tests. Double-ring or flexible-wall permeameters (Figures 23 and 24) can be effective at detecting or minimizing, respectively, side-wall leakage in laboratory tests. Double-ring permeameters give indications of the relative magnitude of the side-wall leakage (i.e., no side-wall leakage is occurring if the flow rate per unit area in both the inner ring and outer ring are the same). Test results should be considered invalid if the flow rates per unit area differ significantly (more than 50%). Flexible-wall permeameters require confining pressure to minimize side-wall flow. This confining pressure can close macropores that may be present in the soil sample, and thereby reduce the hydraulic conductivity below the actual values that would occur under field conditions.

The termination point of a test is critical to the usefulness of the test data for comparison with field data. Saturated hydraulic conductivity tests should be run until steady-state values have been attained. A graph of hydraulic conductivity with time is needed to determine if steady-state hydraulic conductivity values have been obtained.

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